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Sensorimotor experience biases human attention through space and time

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To Luisa, my path

To Fabiano and Rosaria, my backpacks

To Alessandro, my pulse

To Francesca, my travel companion

The most beautiful sea
hasn’t been crossed yet.
The most beautiful child
hasn’t grown up yet.
Our most beautiful day
we haven’t seen yet.
And the most beautiful words
I wanted to tell you
I haven’t said yet…

Nazim Hikmet (1970)

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It is now 4 years since I have started my PhD. Throughout all this time I have experienced and learned quite a lot of lessons. My past self has travelled extensively and has been guided along this journey by enlightened mentors to become my present self. From this familiar hill, I see now more clearly the path I have been walking so far and how my thinking has been taught, influenced and modeled.

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ABSTRACT

Space and time are fundamental dimensions that contribute to make human minds grounded in the physical world. Researchers across the cognitive sciences have recently addressed some key questions about the role of the sensorimotor system in spatial and temporal processing (Chapter 1). The present thesis adds to this debate by exploring the hypothesis that prior directional sensorimotor experience contributes to the human sense of space and time.

The first part of the thesis investigates whether sensorimotor experience influences visuospatial attention. A first study shows that humans have a manual and ocular leftward bias in bisection task in near but not in far space (Chapter 2). This leftward bias, for long mainly explained in terms of a right hemispheric dominance in visuospatial processing, is modulated by directional routines. For instance, individuals from different cultures show visuospatial asymmetries that can predicted by their reading habits (Chapter 3). Similarly, exposure to formal education exerts a strong influence on children's visuospatial attention (Chapter 4). Nonetheless, the impact of cultural routines is further constrained by situational requirements. In fact, bidirectional readers reorient their visual scanning depending on the language of the task at hand (Chapter 5). In line with this, visuospatial biases can be rapidly induced by learned contingent odor-object associations (Chapter 6). On these grounds, it is therefore suggested that biological factors (i.e., hemispheric specialization) interplay with both cultural (i.e., directional scanning associated with language processing) and situational factors (i.e., current constraints imposed by task demands) in modulating visuospatial attention, likely under a hierarchical relationship (Chapter 7).

Since space and time are supposed to be tightly coupled in the human mind by motor actions, the second part of the thesis investigates whether sensorimotor experience influences the spatial representation of time. A first study shows that both finger counting and reading habits are flexibly exploited to map ordered information on the bodily space (Chapter 8). The sensorimotor involvement in representational processes was confirmed in a study showing that eye movements mediate the search and the retrieval of temporally ordered information (Chapter 9). In addition, the view that the egocentric representation of time originates from our walking experience was empirically supported by showing that temporal processing affects step movements along the sagittal space (Chapter 10). Finally, the systematic tendency to experience the future as psychologically closer than the past, derived from our experiential movement through time, was found to be altered in people

with slower walking speed and distorted motion perception, i.e., anxious and depressed individuals (Chapter 11). These studies, therefore, suggest that the processing of time is governed by the same mechanisms that orient our attention in the physical space (Chapter 12).

Overall, this thesis indicates that prior sensorimotor experience affects the way humans attend to space and time (Chapter 13).

Introduction:

THE TANGLE OF SPACE AND TIME

> *'Space (or time) is not something objective and real, nor a substance, nor an accident, nor a relation; instead, it is subjective and ideal, and originates from the mind's nature in accord with a stable law as a scheme, as it were, for coordinating everything sensed externally.'*
>
> – Kant (1908, p. 403)

A defining condition of being human is that we have to make sense of our experience in space and time. Understanding the external reality that underlies our collective experience of the space between things and the time between events is, indeed, paramount to determine human existence. As a consequence, the question about how the sense of space and time originates in the human mind has captivated philosophers and scientists for centuries. This interest reached its culmination in the eighteen century, when the debate between the Leibnizians and the Newtonians, concerning the status of space and time, was resumed by Kant. Newton had previously conceived space and time as real entities, whereas Lebiniz only as relations between objects (Hatfield, 2006). On the contrary, Kant (1781) contended that space and time are nothing but forms of *a priori*, i.e., non-empirical, intuition. In fact, Kant sustained that space and time are not empirical concepts derived from outer experience, but rather that this outer experience is itself possible only through an *a priori* representation of space and time.

Nevertheless, although this definition may be framed in the spirit of innatism, Kant already discussed about a possible influence of the mind modal systems for perception on these *a priori* representations (Zoeller, 1989). This is in line with current views in cognitive sciences, which maintain that brain systems subserving perception (e.g., vision, audition) and action (e.g., movement, proprioception) may be crucial to give rise to the human sense of space and time (Barsalou, 2008; Wilson, 2002). Accordingly, various empirical investigations have started to unveil that the perception of space is not isotropic, but rather it is modulated by the body, the body's relation to the environment and the body's potential for action. Similarly, the perception of time is not predetermined, but rather it is affected by the state of the body and by constraints imposed by the outside world. On these grounds, researchers across the cognitive sciences have recently addressed some key questions about the role of sensorimotor experience in grounding the human sense of space and time.

The present doctoral thesis, therefore, attempts to provide some answers to one of the main mysteries of the study of human cognition: how the human mind constructs the sense of space and time from experience. In particular, the present thesis tries to investigate some central questions on this long-lasting debate, which nevertheless still cries out for clarification, such as: can the human sense of space and time be sought in sensorimotor experience? What is the relationship between space and time in the human mind?

The next two sections will review the theoretical and empirical advances on the understanding of the human sense of space and time, respectively. Yet, they do not attempt to cover the whole literature on the human sense of space and time, but rather they are focused on studies investigating human visuospatial attention and the representation of temporal information. In particular, these two sections are devoted to describe the major achievements in the field, the main issues of debate, and the still open research questions, with a major focus on the role of sensorimotor experience. Finally, the rationale of the studies included in this thesis will be introduced.

1.1. THE FIRST PART: THE SENSE OF SPACE

In everyday life, human attention is constantly shifted toward the left and the right hemifield for targeting extrapersonal salient events (Mesulam, 1999). Thus, in principle, there are obvious benefits in having a symmetrical attentional system devoting equal resources to both hemifields. Nevertheless, we now know that functional asymmetries are quite ubiquitous in humans and that lateralization may offer various advantages (see Vallortigara & Rogers, 2005).

Neurologically healthy individuals, indeed, systematically tend to err toward the left side of the space in simple visuospatial tasks, such as in bisection of horizontal lines, a phenomenon referred to as “pseudoneglect” (Bowers & Heilman, 1980; see for a review, Jewell & McCourt, 2000). This bias has been supposed to be universal and it has been for long explained in terms of hemispheric specialization, according to which visuospatial information would preferentially activate the right cerebral hemisphere that is responsible for the left side of the space (Kinsbourne, 1970). However, these hypotheses are mostly supported by studies involving Western individuals, who read and write in a left-to-right direction. It is therefore possible that reading habits might be determinant in such a lateralized behavior. In line with this possibility, right-to-left readers typically show an opposite performance in visuospatial tasks than Western individuals, challenging an account solely in terms of hemispheric specialization (see for a review, Chokron, Kazandjian & De

Agostini, 2011). Although reading direction has been shown to modulate visuospatial asymmetries, surprisingly this influence has been testified only as a lateralized shift of a single behavioral sign (e.g., line bisection), with lack of proof from pure right-to-left readers. Furthermore, little is known about whether situational requirements (i.e., current constraints imposed by the task at hand) might, in turn, modulate the impact of cultural routines on visuospatial attention. Therefore, the aim of the first part of this doctoral thesis is to systematically explore whether prior directional sensorimotor experience might shape the allocation of visuospatial attention, and whether situational requirements might further constrain visuospatial asymmetries.

1.1.1. Visuospatial neglect

Research on human attention has been for long focused on the investigation of mechanisms underlying neuropsychological disorders such as visual neglect. Unilateral neglect is a neuropsychological syndrome that follows, most frequently, right hemisphere brain damage (see for a review Halligan, Fink, Marhsall & Vallar, 2003). Converging evidence points to the temporal-parietal junction (TPJ) and the inferior parietal lobule (IPL) of the right hemisphere as neural correlates of neglect (see for a review, Vallar, 2001), in line with the supposed role of posterior parietal cortex (PPC) in spatial attention (Corbetta & Shulman, 2011). Furthermore, recent studies in right hemisphere damaged (RHD) patients have reported white matter fiber damage, responsible for a disconnection of a large brain network composed by frontal, temporal and parietal cortex (Bartolomeo, Thiebaut De Schotten & Doricchi, 2007).

Symptoms of unilateral neglect are generally extremely marked. RHD patients often fail to be aware of stimuli presented on their contralesional side, i.e., the left side, and tend to overly attend to stimuli towards their ipsilesional side. Neglect may be so severe to make patients unware of large objects in extrapersonal space and, in some cases, to extend or be confined to personal space (Parton, Malhotra & Husain, 2004). Moreover, patients can fail to use their contralateral limbs (Laplane & Degos, 1983,) and they may be not aware about their perceptual and motor deficits (i.e., anosognosia) (Vallar & Ronchi, 2006).

Different tasks are employed in the assessment of unilateral neglect. A classic paper-and-pencil task that has been extensively used is line bisection. In this task, a line is usually presented on a sheet of paper and the patient is asked to mark the midpoint of the line, i.e., bisect the line. Many RHD patients with left neglect, particularly those with posterior lesions, tend to bisect the line to the right of the true midline (see for a review, Parton et al., 2004). A contralesional bias, however, has been also reported in case of shorter lines, a phenomenon known as "crossover" effect (Halligan & Marshall, 1988).

A further typical task employed in neglect assessment is the cancellation task. In this task, patients are asked to search for and to mark with a pen (i.e., to cancel) visual targets on a sheet of paper. Whereas some types of cancellation tasks have only target items (for instance the Albert's task; Albert, 1973), most of them have targets displaced among various types of distractor items (for instance the "stars cancellation" from the Behavioural Inattentional Test; Wilson, Cockburn & Halligan, 1988). Tipically, RHD patients tend to find and cancel targets only in the right hemispace of the sheet, whereas they ignore and omit targets in the left hemispace, resembling performance in the line bisection task (i.e., neglecting the left space; see for a review, Parton et al., 2004). Critically, visual search of most neglect patients starts in the right hemispace, whereas most healthy individuals start to search for targets in the left hemisapce of the matrix (Azouvi et al., 2002).

1.1.2. Pseudoneglect

Visuospatial performance of neurologically healthy individuals is also not symmetrical. In fact, healthy individuals systematically misbisect visual lines as well as strings of symbols, generally deviating to the left of the veridical center, a phenomenon referred to as pseudoneglect (Bowers & Heilman, 1980; Jewel & McCourt, 2000). This slight, though consistent, bias has been reported also for tactile and kinesthetic modalities. Critically, independently of the specific modality, the size of this bias is generally much smaller than in neglect patients (Jewell & McCourt, 2000).

Similarly, in cancellation task, Western participants typically start their visual search in the left hemispace and, under time pressure, make more omissions in the right side of the space (Manly et al., 2009; Mark, Woods, Ball, Roth & Mennemeier, 2004; Woods & Mark, 2007). Interestingly, the searching strategy has been shown to change over written language acquisition (Brucki & Nitrini, 2008) and over the school years (Woods et al., 2013), shifting the distribution of visuospatial attention asymmetrically to the left side of the space.

1.1.3. The neural bases of pseudoneglect

Visuospatial asymmetries in both RHD patients and healthy individuals have been for long interpreted primarily in terms of hemispheric activation (Bowers & Heilman, 1980; Bradshaw, Nathan, Nettleton, Wilson & Pierson, 1987). According to the hemispheric activation hypothesis, indeed, the spatial nature of the task (e.g., line bisection task or cancellation task) would induce a preferential activation of the right hemisphere leading to an overestimation of the left hemispace in healthy individuals, and thus to the leftward bias known as pseudoneglect. This interpretation is a consequence of the Kinsbourne's activation-orientation theory, which maintains that the attentional resources are located in the contralateral space of the most activated hemisphere (Kinsbourne, 1970, Reuter-Lorenz, Kinsbourne & Moscovitch, 1990). Accordingly, various neuroimaging studies showed a specific activation of the PPC during visuospatial tasks (Fink, Marshall, Weiss, Toni & Zilles, 2002; Foxe, McCourt & Javitt, 2003; Göbel, Calabria, Farné & Rossetti, 2006). Furthermore, a recent study by Thiebaut de Schotten et al. (2011) reported a significant correlation between the degree of anatomical lateralization of parieto-frontal networks and the bias showed on visuospatial tasks. Specifically, the lateralization of the middle pathway of the superior longitudinal fasciculus (SLF II) was strongly correlated with the bias in line bisection as well as with asymmetries in the speed of detection between the right and the left hemispace: the more the SLF II was lateralized in the right hemisphere, the more the behavioral performance was biased toward the left hemispace (Thiebaut De Schotten et al., 2011; see also Thiebaut De Schotten et al., 2005). These findings support, therefore, a hemispheric lateralization also of fronto-parietal networks underlying visuospatial asymmetries (see also Bartolomeo, Thiebaut de Schotten & Chica, 2012).

Together, both behavioral and neuropsychological evidence converge in pointing to an imbalanced hemispheric activation in spatial tasks, partially resulting from the primacy of the right fronto-parietal network in visuospatial and attentional functions (Bartolomeo, Thiebaut de Schotten & Chica, 2012; Corbetta & Shulman, 2011). In support to this neurobiological account of spatial asymmetries, pseudoneglect-like effects have been reported in non-human species, such as in the pecking activity of birds (Diekamp, Regolin, Güntürkün & Vallortigara, 2005) and in the bisection performance of chickens (Diekamp, Manns, Güntürkün Vallortigara & Regolin, 2005; Regolin, 2006; see also Chiandetti, 2011), suggesting a common evolutionary lateralization of spatial attention.

1.1.4. Factors influencing pseudoneglect

Despite the large consensus on a neurobiological basis of visuospatial asymmetries, it is well known that pseudoneglect cannot be solely interpreted in terms of hemispheric activation hypotheses (for a review, see Jewell & McCourt, 2000). Indeed, whereas performance is generally similar across tactile and visual line bisection tasks, several factors have been shown to influence pseudoneglect. For instance, there is a significant effect of age on bisection performance: young individuals tend to make leftward errors, whereas older individuals to make error to the right of the veridical center (e.g., Fujii, Fukatsu, Yamadori & Kimura, 1995). This has been taken as an evidence of age-related changes in cerebral asymmetries subserving the control of visuospatial attention (Jewell & McCourt, 2000).

An effect of azimuthal spatial position is also widely reported in line bisection tasks. Most studies found that lines presented in the right hemispace induced a rightward bias, whereas those presented in the left hemispace produced a leftward bias (Luh, 1995; Reuter-Lorenz, Kinsbourne & Moscovitch, 1990). The influence of the spatial position has been interpreted as another evidence favoring the activation-orientation hypothesis, because the displacement of the line from the midline would likely determine an increase in cerebral activation within the contralateral hemisphere (Kinsbourne, 1970; Reuter-Lorenz et al., 1990). A similar explanation has been also offered for the effects of lateralized cues, which typically consist of letters or geometrical objects placed at one end of the line to be bisected (Fischer, 1994; but see Berti, Maravita, Frassinetti & Umiltà, 1995). On the contrary, the effect of gender on pseudoneglect does not seem to be paramount, although studies that do report sex effects indicate a somewhat stronger leftward error for males than for females (Jewell & McCourt, 2000).

Critically, one of the strongest variables that affects line bisection performance is directional scanning (Jewell & McCourt, 2000). First, the effect of scanning on visual line bisection has been documented by either controlling the direction of gross motor scanning, i.e., asking participants to move the hand from left-to-right or from right-to-left on the line to be bisected, or by controlling the initial starting position of the hand or eyes. Accordingly, different studies showed that individuals typically err towards the side from which a motor or oculomotor scan originates (Chokron, Bartolomeo, Perenin, Helft & Imbert, 1998; Pizzamiglio, Frasca, Guariglia, Incoccia & Antonucci, 1990). Second, an influence of scanning direction has been documented in cross-linguistic studies, which compared performance of individuals with differently-oriented reading and writing systems. For instance, French participants reading from left-to-right err toward the left side of the line, thus showing pseudoneglect, whereas Israeli participants reading from right-to-left err toward the right side (Chokron & Imbert, 1993). Notably, the effect of the habitual reading direction on pseudoneglect does not conciliate with the activation-orientation account (Kinsbourne, 1970), according to which also right-to-left readers should show a leftward bias in line bisection task. In the next section, therefore, we will briefly review some evidence showing the influence of reading direction on visuospatial tasks.

1.1.5. Influence of reading and writing direction on pseudoneglect

Over the years, it has been repeatedly shown that cultural practices, such as reading habits, broadly influence the cognitive system, inducing spatial biases at both perceptual and representational levels. For example, readers from opposite reading directions exhibit directional differences in perception of facial effect (Vaid & Singh, 1989), aesthetic judgment (Chokron & De Agostini, 2000), and direction of stroke movement in free-hand figure drawing (Vaid, Singh, Sakhuja & Gupta, 2002). Moreover, cross-cultural differences linked to the reading and writing system characterize the mental representation of temporal, spatial, action (i.e., semantic) and preference relations (Dobel, Diesendruck & Bölte, 2007; Maass & Russo, 2003; Ouellet, Santiago, Israeli & Gabay, 2010; Tversky, Kugelmass & Winter, 1991). Interestingly, these patterns seem to emerge over school years suggesting the impact of cultural practices in the complex origin of spatial-representational biases (Dobel et al., 2007; Kebbe & Vinter, 2013; see also Fagard & Dahmen, 2003).

Critically, evidence for a cultural shaping of pure visuospatial performance is not lacking. Comparing English, Hebrew and Arabic readers, Nachson (1985) first reported that directional preferences in visual tasks might be a function of both reading and writing habits, or hemispheric asymmetries, or both. Moreover, Abed (1991) reported that in Western, East Asian and Middle Eastern participants, saccades direction, but not location of fixation, was fully predicted by reading habits. More importantly, reading habits have been found to influence line bisection tasks. Chokron and Imbert (1993) showed that Hebrew readers bisected lines to the right of the true center, whereas native French readers bisected lines to the left of the center (see also, Kazandjian, Cavézian, Zivotofsky & Chokron, 2010). Similar patterns have been detected also in preschoolers, where directional asymmetries might originate by observational learning and by trained eye scanning habits in visual perception, indirectly related to reading habits (Chokron & De Agostini, 1995). Language-dependent effects have been reported also in line extension (Chokron, Bernard & Imbert, 1997) and line partition (Zivotofsky, 2004) tasks, although their consistency has been challenged by controversial results (Nicholls & Roberts, 2002). Importantly, previous studies focusing on reading direction effects involved mainly Israeli participants who can hardly be considered monolingual, due to their experience with left-to-right material (i.e., English learning) throughout their education (Chokron et al., 2011).

1.1.6. Current views and open questions

Functional asymmetries in verbal and non-verbal visual tasks have been generally interpreted only in terms of a hemispheric specialization framework. Accordingly, it has been for long hypothesized that in the great majority of right-handers, the left hemisphere is specialized for a number of language-related functions, while the right hemisphere for a number of spatial and motor skills (Bradshaw & Nettleton, 1981; Kimura, 1973). In line with this, asymmetries in visuospatial tasks, such as in line bisection and in cancellation tasks, have been for long interpreted in the light of the activation-orientation account (Kinsbourne, 1970, 1993; Reuter-Lorenz, Kinsbourne & Moscovitch, 1990), which proposes that spatial attention is biased in the contralateral hemispace with respect to the most activate hemisphere (Kinsbourne, 1987).

Critically, this hemispheric hypothesis has been challenged by cross-cultural studies. A first interpretation of visuospatial asymmetries in terms of directional scanning tendencies was already provided by Heron (1957). Subsequent studies supported Heron's hypothesis, suggesting that visuospatial asymmetries would predominantly reflect the tendency to scan information in the direction in which one reads, as revealed by the mirror performance of right-to-left readers. Furthermore, since there is growing evidence in support of an interaction between reading direction and brain function, one may even suggest that well-trained behaviors based on culture can either reinforce or modulate biases arising from hempisheric specialization. Sensorimotor experience of reading and writing routines, indeed, permeate our everyday life across the whole lifespan (see **Figure 1.1** for a schematic illustration).

First, directional preferences might be acquired indirectly by observational learning very early on at preschool age. At this age, most children typically already have spent many hours “reading” stories with their parents, by watching them pointing at lines of a text, and turning pages of books and newspapers. In a culture where text is written and read from left to right, this involves moving one’s eyes and often also a finger along lines of text from left to right. In cultures that use right-to-left scripts, these movements are reversed. Furthermore, children are engaged in many activities in kindergarten that often require the disposition of elements in a preferential direction (e.g., counting or drawing). Second, and critically, directional tendencies are strongly triggered by formal learning of reading and writing practices, which oppositely orients children’s attention and oculomotor system in a left-to-right (Western population) or in a right-to-left direction (e.g., Arabic, Farsi, Hebrew and Urdu population). Moreover, these biases are bolstered by increasing reading experience over the school years. Third, both children and adults experience directional scanning when reading newspapers and books. In the last two decades, this directional experience has been strengthened by the massive use of electronic devices that involve reading of Web component. Indeed, Western individuals generally read Web pages starting with a left-to-right horizontal movement along the upper part of the content area, and proceed with another movement in the same direction in the lower space (Nielsen, 2006). Notably, right-to-left readers’ attention is first focused on the right side of the page, unveiling overall a mirrored reading pattern (Nielsen, 2006).

Nevertheless, to support such a cultural hypothesis of attentional biases future studies are still needed. In fact, the influence of cultural practices on visuospatial attention has been testified only as a lateralized shift of a single behavioral sign (e.g., line bisection) and, importantly, not in pure right-to-left readers. Moreover, little is known about whether the impact of these cultural practices is malleable and sensitive to external cues, as to situational requirements.

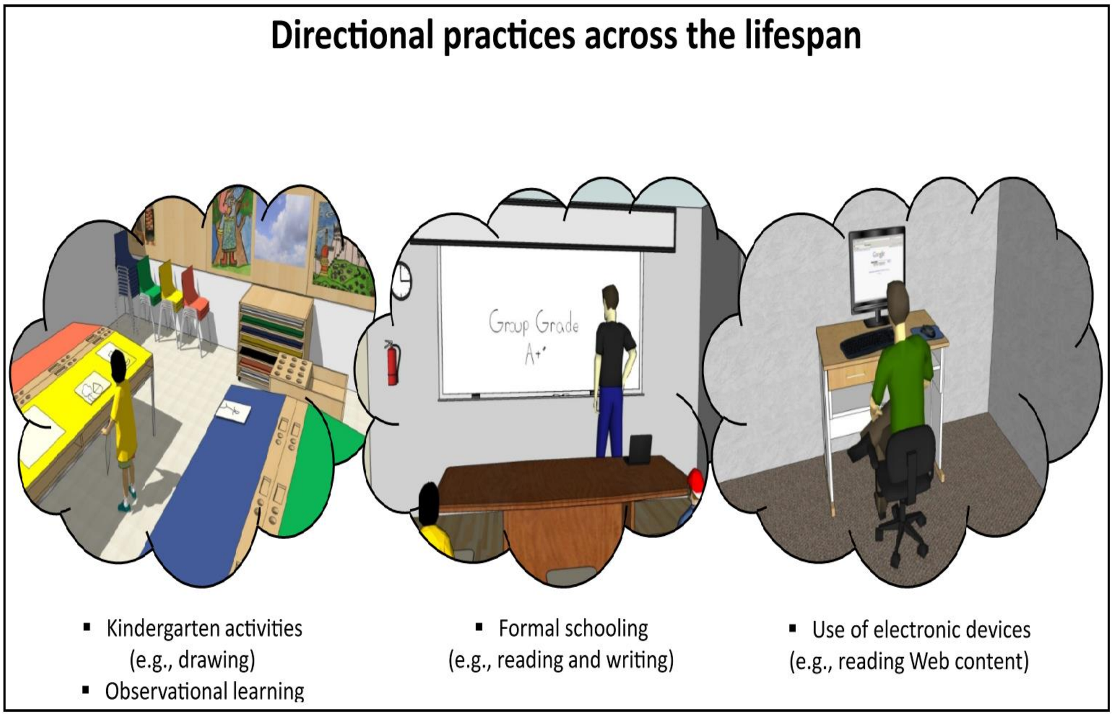

Figure 1.1. Examples of cultural practices involving directional and scanning activities. First, preschoolers might directly experience directional tendencies in drawing and counting, or indirectly, via observational learning. Second, the oculomotor system is trained to scan along a preferential direction, once children are exposed to formal learning of reading and writing. Third, children and adults often make use of electronic devices and, therefore, consolidate a specific directional tendency. Overall, the direction of these practices across the lifespan would significantly influence the allocation of attentional resources in space.

1.1.7. The present work: Sensorimotor experience biases human attention through space

The first part of the thesis investigates whether prior sensorimotor experience influences the allocation of visuospatial attention.

To this aim, in **Chapter 2**, we explored whether humans attend differently to near and far space. Sound evidence, indeed, suggests that our mind represents near and far space differently. For instance, a left-to-right shift in bisection bias with increasing distance has been largely documented in healthy individuals. This rightward shift of bisection bias has been accounted by an unbalanced hemispheric processing, with dorsal stream areas in the right hemisphere that would be mainly responsible for the coding of near space, whereas ventral stream areas for the coding of farther space. In **Chapter 2**, manual and ocular bisections were exploited to further investigate the segregation between near and far space. To this aim, participants were required to perform a bisection task of both simple lines and Judd variants of the Müller-Lyer illusion, presented at three different distances (e.g., 60, 90, 120 cm). Furthermore, since visual lateralized stimuli are mainly processed by the contralateral hemisphere, the spatial location of the lines (e.g., left, centre, right) was also manipulated.

In **Chapter 3**, we investigated whether the leftward bias in near space might be modulated by directional sensorimotor routines. In fact, a growing amount of evidence confirms the influence of reading and writing habits on visuospatial processing, although this phenomenon has been so far testified mainly as a lateralized shift of a single behavioral sign (e.g., line bisection), with lack of proof from pure right-to-left readers. The study presented in **Chapter 3**, therefore, contributed to this issue by analyzing multiple attentional and motor indexes in the visuospatial performance of monolingual Italians (i.e., reading from left-to-right), and monolingual (i.e., reading from right-to-left) and bilingual Israelis (i.e., reading from right-to-left in Hebrew but also from left-to-right in English). Participants were administered a computerized standard star cancellation task and a modified version in which English letters and words were replaced by Hebrew ones. Tasks were presented on a graphics tablet, allowing recording of both chronometric and spatial parameters (i.e., measured in *x, y* vector coordinates) of the performance. In this way, we could directly test the extent to which the activation-orientation account may accommodate cross-linguistic differences.

The influence of reading and writing direction was further explored in **Chapter 4**, by assessing the possible influence of schooling on visuospatial asymmetry. In particular, we aimed at exploring the impact of formal education practices on visuospatial attention in a cancellation task. To this aim, the computerized cancellation task used in **Chapter 3** was administered to Western children before and after exposure to formal reading and writing acquisition.

In **Chapter 5**, we asked whether the impact of cultural routines may be further constrained by situational requirements. Indeed, whereas cultural practices might play a critical role in directing attention in a neutral visual scene, it is likely that attention might be malleable and sensitive to situational cues. The performance of three groups with different reading habits (monolingual left-to-right, monolingual right-to-left and bilingual readers) was compared on three ad-hoc versions of cancellation task: one composed by geometrical shapes, one by Latin letters and one by Hebrew letters. In this way, we explored whether the visuospatial performance may be overall more lateralized in the alphabetical version of the task, compared to the geometrical one. Moreover, we also investigated whether bilingual readers might adopt differently oriented visuomotor search strategy, in the Hebrew and Latin versions of the task.

Finally, in **Chapter 6** we explored the effects induced by a contingent crossmodal association between odors and visual shapes on the allocation of visuospatial attention. The prompt recognition of pleasant and unpleasant odors is, indeed, a crucial regulatory and adaptive need of humans. Answers to unpleasant odors ensure survival in many threatening situations. Notably, although humans typically react to certain odors by modulating their distance from the olfactory source, the effect of odor pleasantness over the orienting of visuospatial attention is still unknown. To address this issue, therefore, we first rapidly trained participants to associate visual shapes with pleasant and unpleasant odors and, then, we assessed the impact of this situational association on a visuospatial task.

Together, the studies reported in the first part of the thesis aim to explore whether prior directional sensorimotor experience might interact with predetermined hemispheric asymmetries subserving the control of visuospatial attention, and whether situational factors might further modulate such interplay.

1.2. THE SECOND PART: THE SENSE OF TIME

Space and time are strictly coupled to each other in both the physical world and in the human mind (Bender & Beller, 2012; Boroditsky, 2000). For instance, we subjectively experience that the passage of time goes along with the passage of space when we move from one place to another. But does this experience of time in a physical space ground our cognition of temporal concepts?

Time is an abstract domain as it is intangible and ephemeral. Interestingly, despite humans have a multitude of senses dedicated to the perception of the outside world, there is no sensory organ uniquely dedicated to time perception. Hence, humans need to compensate the lack of “time” receptors, by grasping this abstract concept through a more concrete dimension. Accordingly, it has been hypothesized that humans may take advantage of spatial relations to represent the more abstract domain of time (Boroditsky, 2000; Casasanto & Boroditsky, 2008). In this sense, direct sensorimotor experience in the physical space might be crucial in giving structure to the abstract concept of time in the human minds. Insofar, however, despite the abundant linguistic and behavioral evidence of a space-time mapping, there is surprisingly little data supporting the idea that our temporal concepts are grounded in space and, more generally, embodied through the sensorimotor system (Kranjec & Chatterjee, 2010). The aim of the second part of this doctoral thesis is, therefore, to explore whether sensorimotor experience grounds the spatial representation of time and whether temporal processing is possibly governed by the same principles subserving spatial processing.

1.2.1. The representation of time

Time perception and time tracking are ubiquitous in nature and are largely graspable by physics. On the contrary, the human conceptualization of time, along with its neural counterpart, is up to date poorly understood. Nevertheless, there is a good agreement on the fact that such representation should be firmly rooted in bodily experience (Boroditsky, 2000; Casasanto & Boroditsky, 2008). Everyday time concepts presumably developed as an efficient way for understanding the rich and complex organization of temporal experience and for expressing these understandings to others, a paramount ability for structuring a narrative self and a narrative culture.

When speaking about time people tend to borrow words and concepts from the domain of space (Alverson, 1994; Clark, 1973). People do so when both describing duration ("a short break") and event location ("in the distant past"), but also when they have to indicate the order of events ("before”) in both spatial and temporal contexts. Interestingly, this tight relationship between space and time goes beyond the literal extension of word meaning, likely because these two dimensions permeate our experience in the physical world. Indeed, it generally takes more time to visually scan larger objects, i.e., objects that occupy more space; similarly, objects that arrive before in time are typically also in front of objects that arrive later; and, finally, when walking we usually leave what we pass by, behind the ego. Hence, we may think and talk about past times as “behind us” because, when we walk, what has already been experienced tends to be located in the space behind us. In line with this, a spatial dimension is often spontaneously exploited in co-speech gestures of temporal expressions (Núñez, Cooperrider, Doan & Wassmann, 2012; Núñez & Sweetser, 2006).

The need for this spatialization of time has been largely accounted for by the conceptual metaphor theory, according to which spatial relational schemas (Johnson, 1987; Lakoff & Johnson, 1980, 1999) play a crucial role in the embodiment of abstract concepts. Schemas, that have been conceived as “boiled down” abstractions of frequently observed spatial and motion patterns, may help us to organize the abstract concept of time by mentally mapping it onto the more concrete domain of as space (Casasanto, 2009). Indeed, space is not only more concrete than time, but it is also intrinsically linked to the processes of motion perception and representation. Along these lines, some empirical views have made the claim that space-time coupling would support an *embodied* view of cognition. Embodied cognition theories (e.g., Barsalou, 2008; Wilson, 2002), in fact, maintain that abstract concepts are structured in the mind by the constraints and experiential couplings imposed by human physiology, and specifically by perception and action. Accordingly, a concept is conceived as embodied when it is cognitively implemented in mental simulation, and when it interacts with sensorimotor transformations and movement planning (Wilson, 2002).

In line with these views, recent years have seen accumulating empirical evidence in support to the proposal that humans process time by mapping it onto a spatial representation (Walsh, 2003; Bonato, Zorzi & Umiltà, 2012). Critically, this evidence does not necessarily imply that the conception of a time line is universal in terms of properties (see Bender & Beller, 2014; Núñez & Cooperrider, 2013). In fact, variability is profound in terms of both the preferred axis and the direction of the supposed mental time line (e.g., Boroditsky, 2001). Before introducing the empirical evidence supporting the mental construal of time, hence, some clarifications are necessary.

1.2.2. Distinctions between time representations

A major difficulty in interpreting the variety of data is due to the common tendency to treat time as a monolith, a propensity that is deeply rooted in the Western philosophical tradition (Sinha, Sinha, Zinken & Sampaio, 2011). To overcome possible misunderstanding and unrealistic generalization some distinctions are, therefore, indispensable.

A crucial difference within the conceptualization of time was made more than a century ago by the philosopher John McTaggart, who proposed the distinction between the so-called “A-series” and “B-series” (McTaggart, 1908). In English, and in many other languages, we can adopt terms as "earlier," "later," "before," "after," to describe a certain event either by relating it to the time of speaking or to its own temporal reference of occurrence. Accordingly, McTaggart (1908) identified the A-series as the representation of events seen from the standpoint of the present moment. An example of such *temporal relational schema* (TRS) is when we speak about events happened "yesterday" or that are supposed to happen "tomorrow" since, in both cases, the reference of our construal is the moment *now* (i.e., the deictic center). Here, the more widespread term "D-Time" (i.e., deictic time) is adopted to designate this particular TRS (see Núñez & Cooperrider, 2013; see also Sinha & Gärdenfors, 2014). In contrast, McTaggart (1908) identified the B-series as the representation of those events that can be conceived solely in terms of their relative order within a sequence of events. An example of such TRS is when we speak of events as happening "earlier" or "later" than other events, where no event is a privileged deictic center. There is no future and no past in this TRS, just earlier-than and later-than relationships. In this case, the more widespread term "S-Time" (i.e., sequence time) is adopted to designate this particular TRS.

As different as they are, D-Time and S-Time share two key features: they both refer to series of ordered temporal events, and they can be both schematically depicted as events that take place along a linear time. Furthermore, although both D-Time and S-Time schemas are almost universal, there is considerable variability in the way they are expressed in different languages (Sinha & Gärdenfors, 2014).

Finally, despite McTaggart's conceptualization of TRSs refers mainly to "series of events," events in real time are also often conceived in terms of duration. Indeed, the concept of duration of temporal event, referred here as "I-Time" (i.e., interval time), refers to a measurable temporal magnitude, such as when we say "one hour" or "the whole day" (see Núñez & Cooperrider, 2013).

It was previously noted that spatial metaphors used for time are abundant in many languages, and this has led cognitive scientists to propose that time is mostly conceptualized in terms of space. It is indeed the case that in speaking about D-Time, S-Time and I-Time we borrow words typically referring to spatial concepts. In the next section we will, therefore, briefly review evidence showing that space is a central dimension in all these three conceptions of time in human mind.

1.2.3. Evidence for the spatial mapping of D-Time

According to the D-Time representation, time can pass or flow. In construing a D-Time representation it is, therefore, possible to adopt an internal or external perspective on the series of events (Núñez & Cooperrider, 2013; see also Sinha & Gärdenfors, 2014). The internal perspective can be exemplified by what seen by a passenger inside a moving train, whereas the external perspective by what seen by a given observer watching the moving train from another point of view. In this sense, D-time representation exhibits two construals: one with an internal perspective, where the deictic center, i.e., the ego, is inherently collocated with "now" in the series, and a second one with an external perspective, where the deictic center is externally located. There is growing empirical evidence that all languages show, at various levels, some lexical resources that capture both these D-Time series in terms of space.

First, the representation of external D-Time series along the horizontal space has been largely documented (see for a review Bonato et al., 2012; Núñez & Cooperrider, 2013; see **Figure 1.2** for a schematic illustration of external D-Time). In Western cultures, indeed, stimuli referring to "before" or "past" are preferentially associated with the left side of the space, whereas those referring to "after" or "future" are associated with the right side of space (in which the deictic center - the ego - is inherently collocated with *now*). This association is mainly documented by a faster categorization of temporal information when the response mapping is congruent with the left-past and right-future association (Santiago, Lupáñez, Pérez & Funes, 2007; Torralbo, Santiago & Lupiáñez, 2006; see also Bottini, Crepaldi, Casasanto, Crollen & Collignon, 2015). Notably, this preference is sensitive to cultural habits, as it reverses in right-to-left readers. People reading from right-to-left, indeed, are faster in detecting words referring to the past with a right effector, whereas they are faster in detecting future-related words with a left effector (Fuhrman & Boroditsky, 2010; Ouellet et al., 2010; Tversk et al., 1991; see **Figure 1.2**).

Similarly, the direction of the reading and writing system accounts for the vertical arrangement of temporal concepts. For instance, Mandarine speakers exhibit a vertical spatial layout for temporal representation, whereas English speakers do not (Boroditsky, Fuhrman & McCormick, 2011; Miles, Tan, Noble, Lumsden & Macrae, 2011). These results, therefore, suggest that kinematic patterns of ocular (i.e., reading) and oculomotor (i.e., writing) routines can provide the ground for a preferential spatial representation of time. In line with this, a recent study found that a brief exposure to a new orthography can temporarily change the direction and orientation of the time line, even when the new space-time mapping contradicts the reader's usual mapping (Casasanto & Bottini, 2014).

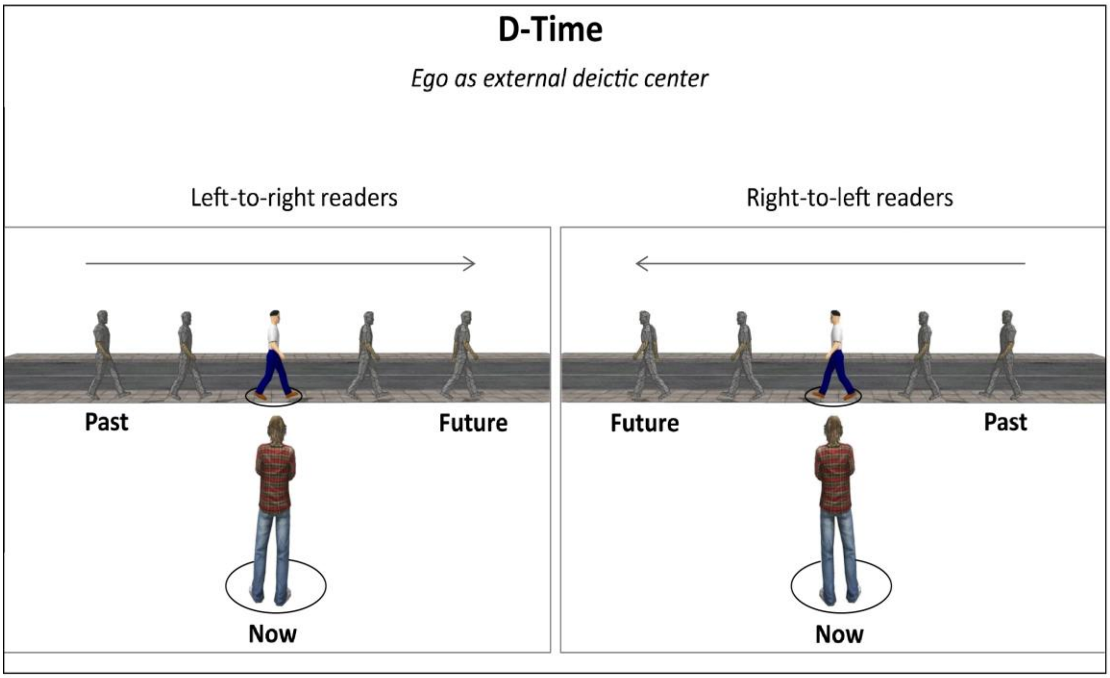

Figure 1.2. Illustration of external D-time. In this construal of time, the present moment "now" is taken as the reference point and it is represented from an external perspective (i.e., the deictic center is displaced to an external locus). Among left-to-right readers time is conceived as flowing from left (past) to right (future), whereas in cultures where reading and writing flow from right to left, time is also represented as flowing leftward.

Evidence reporting an internal representation of D-Time series along a sagittal axis is also not missing (see **Figure 1.3** for a schematic illustration of internal D-Time). The typical sagittal representation of time conceives past and future events as behind and as in front of the ego, respectively. This representation has been named as the *moving ego* metaphor and it is supposed to reflect the way we move in space because, when we walk, what has already been experienced in time tends also to be located behind us in space (Clark, 1973). There is, however, a complementary schema, which conceives the speaker as stationary and the time as moving, i.e., *moving time* metaphor (Clark, 1973). Our discussion here will be focused on the more widespread *moving ego* metaphor of time, rather than on the *moving time* metaphor. Nevertheless, evidence in support of the latter is available. For instance, it has been shown that priming spatial perspectives or exposing participants to real motion may affect the external representation of D-Time series (Boroditsky, 2000; Boroditsky & Ramscar, 2002).

Data on spontaneous gestures support the adoption of the sagittal axis in communicating about deictic time, although with flexibility (i.e., no marked preference for a back-to-front or a front-to-back time line; see Casasanto & Jasmin, 2012). The sagittal D-Time is also supported by data on postural bodily sway (Miles et al., 2010) and by findings from congruency priming tasks requiring motor responses along the sagittal space (e.g., Torralbo et al., 2006; Ulrich et al., 2012). In fact, postural sway during a mental time travel is congruent with the direction of mental metaphors, i.e., Western individuals move slightly backward when thinking about their past and move forward when thinking about their future (Miles, Nind & Macrae, 2010). Furthermore, responses to past- and future-related sentences were found to be faster in German speakers when they have to move a slider back and forth, respectively (Ulrich et al., 2012; see also Hartmann & Mast, 2012).

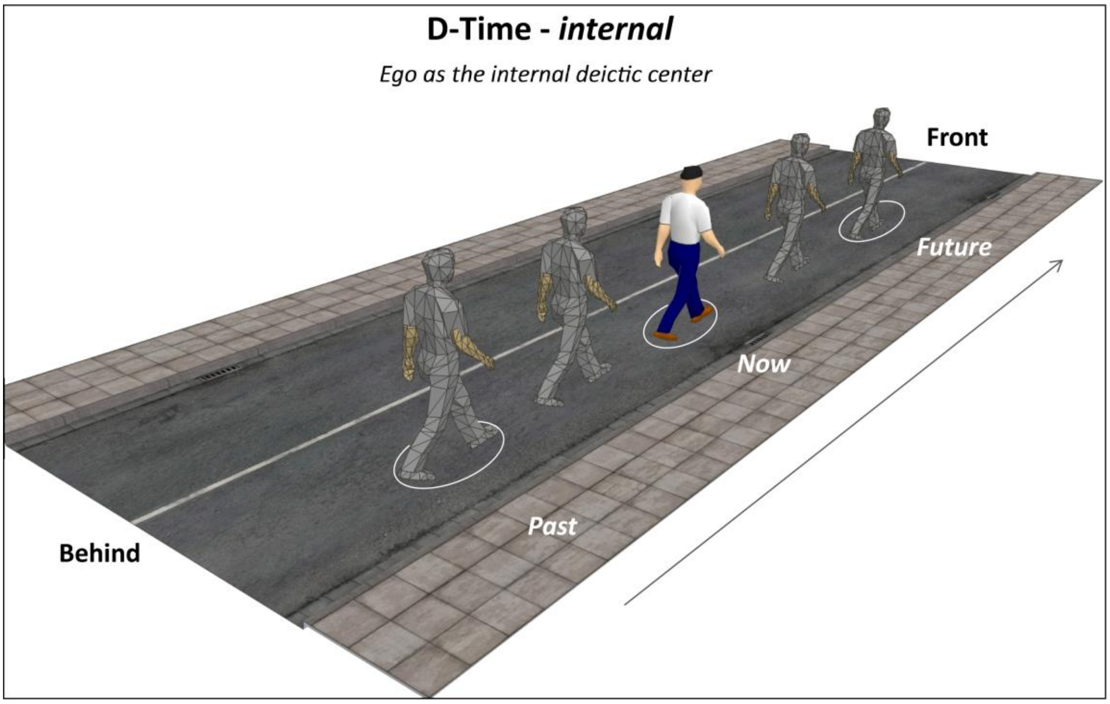

Figure 1.3. Illustration of internal D-time. In this construal of time, the deictic center - the ego - is inherently collocated with "now" in the series. Among most cultures (see for a review, Núñez & Cooperrider, 2013), D-time is conceived as flowing along a sagittal space, with past represented behind the ego and future as in front of it.

1.2.4. Evidence for the spatial mapping of S-Time

S-time relations can also be specified by using spatial metaphors and can, as well, elicit space-time compatibility effects (see **Figure 1.4** for a schematic illustration of S-Time). For instance, when Western participants perform a positional judgment task with letters of the alphabet, months of the year and days of the week, the first elements of the sequence are typically associated with the left side of the space, whereas the last elements with the right space (Gevers, Reynvoet & Fias, 2003). Notably, as for the D-Time series, reading habits significantly influences the direction of the spatial layout. Indeed, reversed compatibility-effects (i.e., right-to-left) were observed with Hebrew letters, indicating that people's orientation of S-Time series also relies on directional routines and on cultural practices (Shaki & Gevers, 2011).

Interestingly, this spatial arrangement of S-Time has been observed not only with overlearned sequences, but also with newly learned sequences. First, Previtali et al. (Previtali, de Hevia & Girelli, 2010) showed that newly learned ordered sequence of words conveys a spatial coding, indicating that this information is represented in memory along an oriented continuum, as for other overlearned sequences. Similarly, when individuals have to categorize the items of a story as preceding or following a reference item in the sequence, they are faster in responding to earlier items with the left hand and to later items with the right hand (Santiago, Román, Ouellet, Rodríguez & Pérez-Azor, 2010). In line with this, recent evidence has shown that serially-ordered verbal information is encoded along a spatial dimension (van Dijck & Fias, 2011). In particular, short sequences of numbers and words memorized in working memory were found to be associated to space: items presented at the beginning of the memorized sequence were responded to faster with the left hand-side, while items from the end were responded to faster with the right hand-side (van Dijck & Fias, 2011).

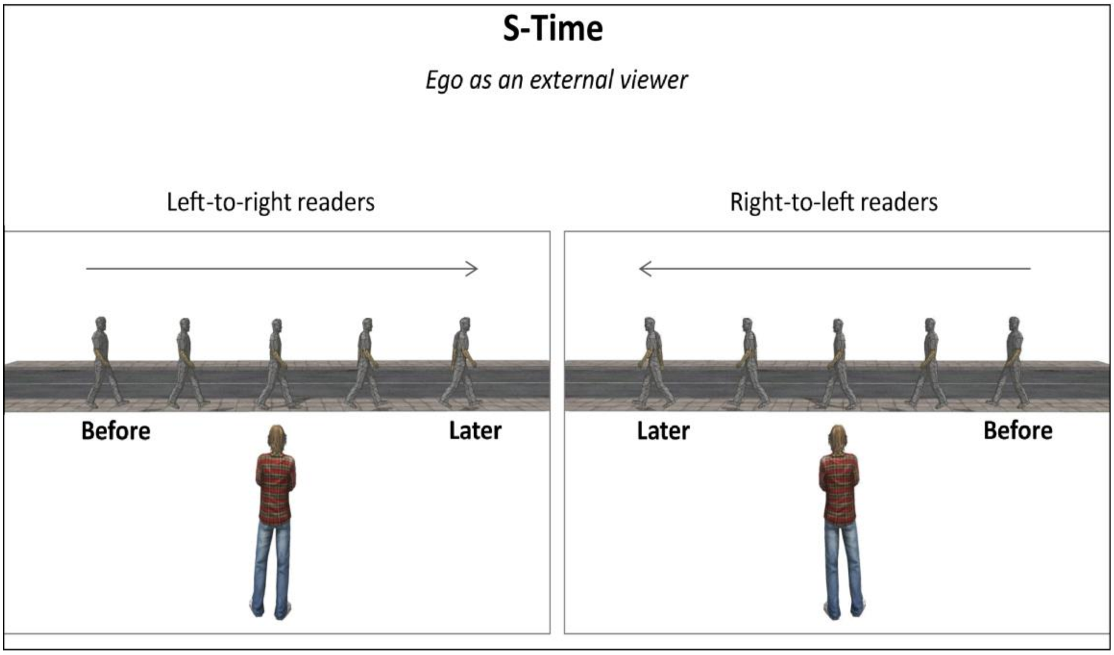

Figure 1.4. Illustration of S-time. In this construal of time, events can be conceived solely in terms of their order in the sequence. There is neither future nor past in this construal, just earlier-than and later-than relationships. As for the external D-Time, the direction of this representation depends largely on the direction of reading and writing habits.

1.2.5. Evidence for the spatial mapping of I-Time

The spatial construal of I-Time in language is documented by different linguistic expressions, such as “A long period of time” (see **Figure 1.5** for a schematic illustration of I-Time). Accordingly, previous studies demonstrated that perception of distance and of duration are tightly associated to each other (e.g., Cohen, Hansel & Sylvester, 1954; Zäch & Brugger, 2008). Notably, it has been shown that representations of space and time are not symmetrically dependent on each other, but rather distance influences duration estimates more than the other way around (Casasanto & Boroditsky, 2008). This evidence also speaks in favor of an embodiment of time, as temporal information would be grounded on perception and representation of more physical dimensions, such as space.

Interestingly, a systematic association between duration and space has also been reported, with short and long durations that prime faster responses with the left and the right hand, respectively (Ishihara, Keller, Rossetti & Prinz, 2008; Vallesi, Binns & Shallice, 2008). This phenomenon, labeled as a Spatial-Temporal Association of Response Codes

(STEARC) effect (Ishihara et al., 2008; Vallesi et al., 2008), is also affected by cultural factors, such as reading and writing direction (e.g., Vallesi, Weisblatt, Semenza & Shaki, 2014).

Notably, estimates of time duration are particularly recurrent in everyday life when people have to judge distances in time from the viewpoint of the ego, such as in the expression "The summer break is very far from now". Interestingly, there is evidence showing that movements in sagittal space can affect the I-Time. In fact, a recent study by Caruso et al. (Caruso, Van Boven, Chin & Ward, 2013) showed that people do not perceive equally the psychological distance between past or future events from the present. Specifically, a systematic tendency to experience the future as psychologically closer than the past was reported (Caruso et al., 2013). An experiment manipulating the direction of participants' apparent physical movement suggests that this systematic tendency is a consequence of experiential movement through time (Caruso et al., 2013). In particular, this temporal asymmetry would be influenced by the physical egocentric motion in space, experienced primarily in everyday walking behavior. Because people perceive objects as closer when they physically approach them in space (Lewin, 1935), patterns of perceived movement through space would be similar to patterns of perceived movement through time, giving arise to the reported temporal asymmetry.

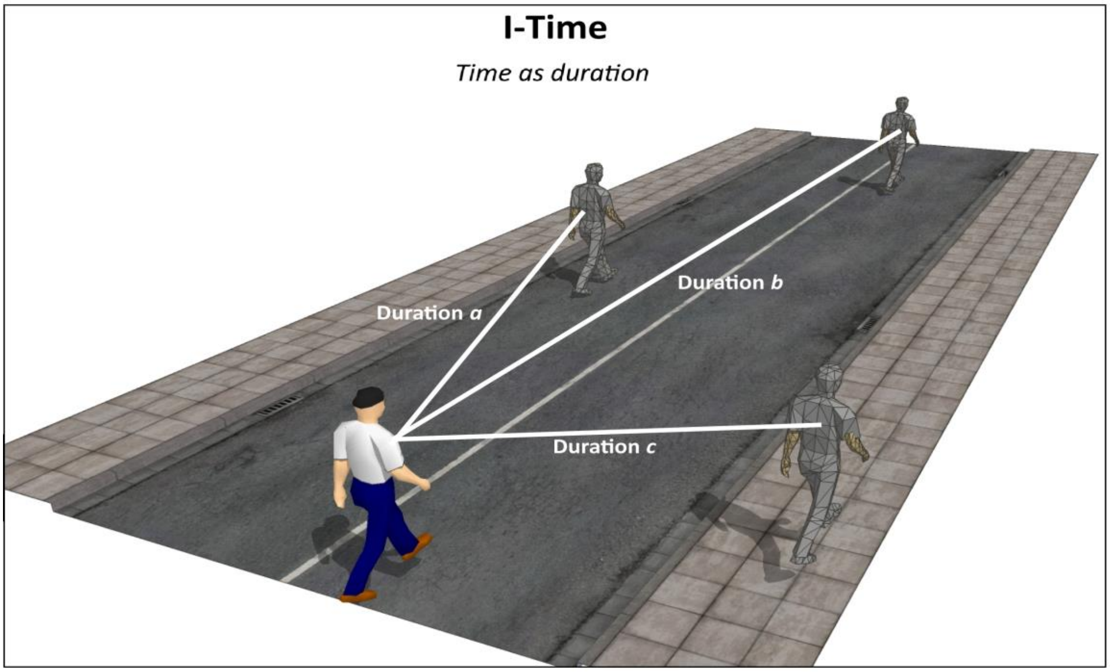

Figure 1.5. Illustration of I-time. This construal of time refers to durations, either subjective or objective temporal magnitudes, which can be compared to each other.

1.2.6. Visuospatial attentional shifts along the representation of time

The multiple response-side compatibility effects reported in the literature clearly speaks about a preferential representation of time along spatial coordinates. Critically, increasing evidence points to a key role of visuospatial attention in accessing such representation. Indeed, it was shown that time-related words used as cues orient spatial attention according to a left-to-right representation of time (Ouellet, Santiago, Funes & Lupiáñez, 2010; see also Weger & Pratt, 2008). Furthermore, retrieving an item from a newly acquired ordered sequence has been shown to be mediated by covert spatial attention (van Dijck, Abrahamse, Majerus & Fias, 2013), since the detection of a visual target appearing in the left or in the right side of the space was modulated by the serial position of a previous memorized item acting as a prime. Specifically, the later the position of an item in the memorized sequence, the faster the detection of the target in the right side of the space (van Dijck, Abrahamse, Acar, Ketels & Fias, 2014; van Dijck et al., 2013). The functional involvement of spatial processing in serial order was confirmed in a recent study where retrieval was found to be facilitated by visuospatial priming and, more specifically, by task-irrelevant exogenous spatial cues (De Belder, Abrahamse, Kerckhof, Fias & van Dijck, 2014).

In line with the involvement of attentional resources in temporal processing, responses to auditory temporal durations are affected by task-irrelevant visuospatial cues, i.e., left cues inducing an underestimation of temporal duration and *vice versa* (Di Bono et al., 2012). More evidence comes from studies with healthy participants using both prismatic adaptation and optokinetic stimulations, which are known to modulate visuospatial attention. In fact, a first study by Vicario et al. (Vicario, Caltagirone & Oliveri, 2007) showed that moving attention towards the right hemispace by means of optokinetic stimulation induces time overestimation, whereas moving attention towards the left hemispace induces a trend towards time underestimation. Following a similar mechanism, the spatial representation of time is influenced by prismatic adaptation in both a reproduction and in a bisection task (Frassinetti, Magnani & Oliveri, 2009).

Finally, further evidence comes from studies involving RHD patients with left spatial neglect, i.e., a syndrome whereby participants typically fail to orient towards the contralesional space (including in some cases also representational space; see for a review, Heilman, Watson & Valenstein, 1993). For instance, Saj et al. (Saj, Fuhrman, Vuilleumier & Boroditsky, 2014) found that RHD patients suffering from spatial neglect do not only neglect the left side of space but also the left side of the mental time line, i.e., past events.

Moreover, RHD patients present an underestimation of temporal durations that goes along their contralesional deficits in spatial-representational hemispace (Oliveri, Magnani, Filipelli, Galante & Frassinetti, 2013). Furthermore, two recent studies (Magnani, Oliveri, Mancuso, Galante & Frassinetti, 2011; Olivieri et al., 2013) showed a crucial influence of prismatic adaptation, and thus of spatial attention, on temporal estimation tasks.

1.2.7. The neural bases of time representation

Neuropsychological evidence has for long supported a common representation of space and time in the human brain (Basso, Nichelli, Frassinetti & di Pellegrino, 1996; Critchley, 1953). Importantly, a recent theory has proposed a comprehensive neural hypothesis to account for the observed space-time interactions ("A Theory Of Magnitude - ATOM"; Walsh, 2003; Bueti & Walsh, 2009).

According to ATOM, prothetic dimensions (i.e., concerned with quantitative variation; Stevens, 1957), such as quantity, space, and time, all share a magnitude code. In particular, these dimensions would mutually operate on similar magnitude representations, because of the need to learn about the environment for acting on it (Walsh, 2003). In fact, Bueti and Walsh (2009) suggested that humans learn about space-time associations while planning and performing actions. Hence, the same brain networks, and the underlying cognitive mechanisms, for spatiotemporal transformations involved in action would be co-opted for developing a system devoted more generally to magnitude processing. This would, in turn, facilitate the quantification process, because the same metrical map used to measure all quantitative information (i.e., quantity, space and time) would have a spatial nature. This magnitude-related information would be, therefore, processed by a generalized system located in the inferior parietal cortex (Bueti & Walsh, 2009).

In line with ATOM, the parietal cortex is largely involved in temporal processing (e.g., Magnani, Oliveri, Mangano & Frassinetti, 2010; Oliveri, Koch, Salerno, Torriero, Gerfo & Caltagirone, 2009). Moreover, PPC has been shown to mediate the effects of prismatic adaptation on the representation of time (Magnani, Mangano, Frassinetti & Oliveri, 2013; see also Magnani et al., 2014). Notably, a recent fMRI study (D'Argembeau, Jeunehomme, Majerus, Bastin & Salmon, 2015) investigated the neural substrates of temporal order, by asking participants to determine which of two past or future events occurred before the other. Results showed that the parietal cortex and, more specifically, the intraparietal sulcus

(IPS) contributed to order processing in autobiographical thought. This neural involvement is in line with the view that IPS supports time-space mappings (Bueti & Walsh, 2009). Interestingly, results from D'Argembeau et al. (2015) further showed that IPS was recruited to a greater extent when the events to be ordered were closer to each other in time. This distance effect fits with the IPS activity during the processing of overlearned ordered elements, such as numbers and letters (Fias, Lammertyn, Caessens & Orban, 2007; Pinel, Dehaene, Riviere & LeBihan, 2001), and of newly-learned sequences (Attout, Fias, Salmon & Majerus, 2014), that are all represented along a spatial continuum. This and other related findings have, therefore, led to the view that the IPS supports domain general ordinal processes that allow coding for temporal and serial order in various task domains (Attout et al., 2014).

Nevertheless, it is worth noting that time processing is not confined in the parietal lobes. Indeed, a growing number of studies indicates that remembering the past and imagining the future recruit a common "core" network of frontal, parietal, and temporal regions (Addis, Wong & Schacter, 2007; Bueti, Walsh, Frith & Rees, 2008; Suddendorf & Corballis, 2007). Moreover, a specific role of the hippocampus in the retrieval of temporal information has been documented (Hassabis & Maguire, 2007).

1.2.8. Current views and open questions

To date, two main proposals accounting for humans space-time interactions have been advanced: the ATOM (Walsh, 2003; Bueti & Walsh, 2009) and the attentional mental time line (MTL) proposals (Bonato et al., 2012). Despite both proposals have many overlapping features and identify the locus of the neural networks subserving space-time interactions in the parietal lobe, they provide a different interpretation of this neuro-functional association. For instance, ATOM underlines the importance of an action-related common system for magnitude, whereas MTL supports the view that the spatial maps were "culturally recycled" (Dehaene & Cohen, 2007) for the processing of temporal information.

In particular, ATOM speaks in favor of a bidirectional interplay between the processing of different magnitudes. Sensorimotor transformation for action preparation, but not spatial representations, would be the common metric for all magnitudes (Walsh, 2003; Bueti & Walsh, 2009). On the contrary, the MTL proposal specifically suggests that time is represented along a spatial dimension. In this sense, visuospatial attention would be critical in orienting our mind's eye through the representation of temporal information (Bonato et al., 2012). ATOM, on the other hand, does not emphasize the role of visuospatial attention, but rather an action-related common system for quantity, space and time.

As can been inferred from above, however, the boundaries between ATOM and MTL are difficult to grasp, as both sensorimotor experience and attention would play to some extent a crucial role in space processing. Here we aim to conciliate these two proposals, by hypothesizing that prior sensorimotor experience is essential for shifting visuospatial attention in temporal processing. In particular, we suggest that prior directional sensorimotor experience in space (e.g., reading and writing, counting on body parts, locomotion) influences the processing of temporal information, with visuospatial attention being the medium for determining the spatial mapping of time.

1.2.9. The present work: Sensorimotor experience biases human attention through time

Since space and time are supposed to be tightly coupled in the human mind by motor actions, the second part of the thesis investigates whether sensorimotor experience influences the spatial representation of time. This was done by emphasizing both the role of prior experience and current requirements imposed by the task at hand, as well as by adopting experimental paradigms that operationalized time in terms of space.

In particular, in **Chapter 8**, we explored the influence of multiple directional sensorimotor routines, such as finger counting and reading habit, in the mapping of S-Time (i.e., overlearned sequences) on the bodily space. In fact, the literature supports finger counting and reading habits as determinant cultural visuomotor routines for representing ordinal information in space. However, no study has so far investigated whether the spatial representation of numbers and, more generally, of ordinal sequences relies on finger counting, on reading direction or on an interplay of both. Hence, in this first study we directly explored the strength of the "finger-representation account" and of the "reading-representation account" in a series of three experiments, by requiring participants to map ordinal information to all fingers of the dominant hand. Moreover, to emphasize the impact of reading direction on the spatial representation of ordinal information, Israeli participants reading both from left-to-right and from right-to-left were involved. Critically, we manipulated both the direction of the mapping and the language of the verbal information. More specifically, a finger-mapping compatibility task was adopted in three experiments to explore the spatial representation of numerical (digit numbers and number words), and non-numerical (days of the week, presented in Hebrew and in English) ordered sequences.

The sensorimotor involvement in representational processing of S-Time (i.e., newly learned sequences) was further explored in a second study (**Chapter 9**), in which we asked whether travelling through serially-ordered verbal memories exploits overt visuospatial attentional resources. Indeed, while previous studies have shown that covert spatial attention is engaged in accessing the temporal representation, there is no direct proof of sensorimotor changes in overt orienting during temporal and serial processing. To this aim, in a three-phase behavioral study, five single-digits were presented sequentially at one spatial location in a first phase, whereas recognition and verbal recall were tested in a second and third phases, respectively. Participants were required to respond verbally in both the recognition and the recall phases. Importantly, to investigate the role of the oculomotor system in mediating between space and serial order, we measured spontaneous eye movements at the onset of the verbal response.

We next explored the sensorimotor involvement during the processing D-Time (i.e., past and future) along the sagittal space (**Chapter 10**). Insofar, indeed, there is no direct evidence supporting the role of the sensorimotor system in the sagittal representation of time, despite this construal is supposed to originate from our walking experience in the physical world: as people typically walk in forward direction, they consequently move forward through both space and time. On these grounds, here we reasoned that if the egocentric representation of time originates from walking, temporal processing should affect step movements along the sagittal space. Participants were, therefore, asked to categorize auditory words referring either to the past or to the future by means of whole-body single-step movements, in different conditions, with kinematic parameters of the performance that were acquired through an optoelectronic system.

Finally, in **Chapter 11**, we explored the possible effects of emotion and altered sensorimotor experience on the representation of I-Time (i.e., subjective distance of events in time). In particular, we investigated whether the typical tendency to experience the future as psychologically closer than the past, derived from our experiential movement through time, is distorted in anxious and depressed individuals, who are known to have slower walking speed and distorted motion perception.

Together, these studies aim to explore whether habitual sensorimotor transformation for action affects temporal processing, by shifting attention through a spatiotemporal continuum.

PART I: THE SENSE OF SPACE

ASYMMETRIES IN NEAR AND FAR SPACE:

A manual and ocular study of line bisection and Judd illusion

Chapter adapted from:
Rinaldi, L., Bertolini, G., Bockisch, C.J., Maravita, A., Brugger, P. & Girelli, L., (*submitted*). Asymmetries in near and far space: A manual and ocular study of line bisection and Judd illusion.

2.1. INTRODUCTION

The perception of the space surrounding our body is a key aspect for interacting with the external world. In everyday life, we need to perceive the location of our body with respect to an external reference point in order to program actions within a reasonable distance. As such, it has been repeatedly shown that the representation of near, peripersonal, space differs from the representation of more far, extrapersonal, space (for a review see, Halligan et al., 2003). Beyond this representational dissociation, there is now growing evidence showing that different areas of the human brain are responsible for the coding of near and far space (e.g., Longo, Trippier, Vagnoni & Lourenco, 2015; Mahayana, Tcheang, Chen, Juan & Muggleton, 2014; Valdés-Conroy, Sebastián, Hinojosa, Román & Santaniello, 2014). Evidence for a distinction between near and far space was early reported in monkeys with unilateral ablation of area 6 (postarcuate premotor cortex) resulting in a profound neglect of the contralesional near space, whereas ablation of area 8 (frontal eye field) resulted in a neglect of the contralesional far space (Rizzolatti, Matelli & Pavesi, 1983). A corresponding dissociation was later demonstrated in humans, starting from the seminal work by Halligan and Marshall (1991). A right-brain damaged patient suffering from left visuospatial neglect, a neuropsychological syndrome whereby patients fail to explore the contralateral side of space (Heilman et al., 1993), did show a severe neglect of the left near space, but critically, no neglect symptoms were found in far space (Halligan & Marshall, 1991). The opposite dissociation, i.e., neglect in far but not near space, has been reported later on, corroborating a fundamental distinction between the neural mechanisms underlying the control of spatial attention in near and far space (Berti & Frassinetti, 2000; Cowey, Small & Ellis, 1994; Keller, Schindler, Kerkhoff, Von Rosen & Golz, 2005; Pizzamiglio et al., 1989; Vuilleumier, Valenza, Mayer, Reverdin & Landis, 1998).

Evidence in support of a near/far space dissociation comes also from studies with healthy individuals. Indeed, the slight leftward bias characterizing the bisection of visual lines, referred to as pseudoneglect (Bowers & Heilman, 1980; for a review see Jewell & McCourt, 2000), is known to be modulated by visual distance (McCourt & Garlinghouse, 2000). While participants show pseudoneglect in near space, a gradual shift of the subjective midpoint to the right of the objective centre has been consistently reported with increasing viewing distance (Bjoertomt, Cowey & Walsh, 2002; Heber, Siebertz, Wolter, Kuhlen & Fimm, 2010; Longo & Lourenco, 2006; Varnava, McCarthy & Beaumont, 2002). Interestingly, the extent of this rightward transition has been taken as an index of plasticity of the near space.

In fact, line bisection has been exploited to investigate the remapping of space, such as the extension of near space to far space by tool use (Gamberini, Seraglia & Priftis, 2008; Longo & Lourenco, 2006), as well as the contraction of near space by increasing the arm's effort with heavy wrist weights (Lourenco & Longo, 2009). It is worth noting that, along with studies replicating these findings, there are studies which failed to report effects of viewing distance on visuospatial asymmetries (e.g., Cowey, Small & Ellis, 1999; Thomas & Elias, 2010).

The mechanisms underlying the rightward shift of the bisection bias with increasing viewing distance remain poorly understood. Recently, Longo et al. (2015; see also Longo & Lourenco, 2006) attempted to clarify this phenomenon by harking back to the activation-orientation account (Kinsbourne, 1970, 1993; Reuter-Lorenz et al., 1990), which proposes that spatial attention is biased towards the contralateral hemispace with respect to the most activate hemisphere, a tendency stronger for the left than for the right hemisphere (Kinsbourne, 1987). In line with this account, when individuals perform a bisection task, a preferential activation of the right hemisphere would lead to a leftward attentional bias (Bultitude & Davies, 2006; Loftus & Nicholls, 2012). Accordingly, various neuroimaging studies showed an activation of the PPC during visuospatial tasks (Fink, Marshall, Weiss, Toni & Zilles, 2002; Foxe, McCourt & Javitt, 2003; Göbel, Calabria, Farné & Rossetti, 2006). Critically, the right hemisphere dominance and the relative leftward bisection bias would result from a baseline rightward bias and a counteracting leftward tendency induced by the activation of areas in the right hemisphere, specialized for near space (Longo et al., 2015). Hence, the leftward bias induced by the dominant right hemisphere would mainly characterize the processing of the near space. As individuals process information at farther distances, the left hemisphere would play a more active role, thus minimizing pseudoneglect and biasing attention to the right hemispace. According to this hypothesis, right-lateralized negativity over the occipito-parietal scalp induced by a visuospatial attention task has been reported to depend on viewing distance (Longo et al., 2015). Specifically, the maximum magnitude of this negativity was found in near space, whereas it was reduced in far space (Longo et al., 2015). Likewise, a recent study using repetitive transcranial magnetic stimulation (rTMS) on healthy participants reached similar conclusions. In particular, rTMS over both the right PPC and right precuneus induced neglect-like effects in near space (i.e., a rightward shift with respect to the leftward bias in the no-stimulation condition), but not in far space (Mahayana et al., 2014). Overall, these studies indicate that the right posterior parietal cortex and the right precuneus are involved in the control of visuospatial attention in near space, pointing to a critical role of the dorsal visuomotor processing stream. Indeed, along with the hemispheric imbalance in processing stimuli at different distances, a segregation between the dorsal stream areas, that would code mainly information in near space, and the ventral stream areas, that would code information in far space, was previously reported (Bjoertomt et al., 2002; Weiss et al., 2000; Weiss, Marshall, Zilles & Fink, 2003; see also Valdés-Conroy et al., 2014).

Whereas the right parietal cortex has been claimed to be responsible for the slight leftward advantage in visuospatial attention, the neural mechanisms underlying the processing of visual illusions seems to be located in different areas of the human brain (see for a review, Vallar & Daini, 2006). Evidence supporting this distinction comes from studies using the Müller-Lyer illusion and its variants (Müller-Lyer, 1889). In the Müller-Lyer illusion, oriented arrowheads placed at line ends induce a misperception of the line length. In particular, inward-oriented arrowheads reduce the perceived length of the line, while outward-oriented arrowheads prolong it. Both neuropsychological (Daini, Angelelli, Antonucci, Cappa & Vallar, 2002; see also Mancini, Bricolo, Mattioli & Vallar, 2011) and neuroimaging (Weidner & Fink, 2007) data indicate that bilateral occipito-temporal cortex is involved in the processing of the visual illusion. These results were further strengthened by a recent rTMS study on healthy participants (Mancini, Bolognini, Bricolo & Vallar, 2011). Mancini et al. (2011) found that rTMS over both the left and the right occipito-temporal cortex interfered with the processing of the visual illusion, while critically the superior parietal stimulation had no effect on the performance (cf. see Weidner, Boers, Mathiak, Dammers & Fink, 2010). This pattern of results, along with data on neglect patients (Vallar & Daini, 2006), indicates that the mechanisms underlying the visual Müller-Lyer illusion are tightly linked to mechanisms responsible for object perception and, thus, linked to the ventral visual stream. On the contrary, dorsal stream areas would play a limited role in the processing of the visual illusion, by integrating these object representations into spatial reference frames only subsequently in time (Weidner et al., 2010). Hence, the processing of the illusion-related visual features would be partially independent from the mechanisms subserving pure visuospatial information processing.

Despite their potential explanatory power, eye-tracking methods have seldom been used to investigate visuospatial asymmetries in near space. Eye-tracking allows the investigation of the cognitive processes underlying task performance and, importantly, can inform about the focus of participants' attention (Duchowski, 2007). More critically, the "eye-mind" assumption argues that the eye fixation is generally located where the visual scene is currently processed (e.g., Just & Carpenter, 1980; Rayner & Pollatsek, 1989; for a critical view see Irwin, 2004). Following this rationale, a few studies have tried to investigate the ocular behavior during line bisection-like tasks. Typically, these have focused on fixation behavior (e.g., Barton, Behrmann & Black, 1998; Ishiai, Furukawa & Tsukagoshi, 1989), although more recent investigations have also exploited saccadic eye movements, that would better gather the overall visuospatial performance on line bisection and related tasks (Thomas, Loetscher & Nicholls, 2012). However, the use of different experimental procedures has led to contrasting results. In fact, whereas some studies reported the expected pseudoneclect, i.e., a leftward bias, also for ocular behavior (Cavézian, Valadao, Hurwitz, Saoud & Danckert, 2012; Hurwitz, Valadao & Danckert, 2011), others found that eye movements during line bisection are biased slightly to the right of the objective centre (Elias, Robinson & Saucier, 2005; Leonards, Stone & Mohr, 2013). We note, however, that most of these studies did not use line bisection, but rather adopted the greyscales task (Nicholls, Bradshaw & Mattingley, 1999; Mattingley et al., 2004), which requires a forced-choice comparison of the luminance of two overall equiluminant rectangles, one with an increasing, the other with a decreasing brightness gradient from left to right (Elias et al., 2005; Thomas, Loetscher & Nicholls, 2014). Other researchers (e.g., Thomas et al., 2012) used the landmark task, which requires a forced-choice comparison of the length of two segments of off-centre prebisected lines. Although these tasks have been widely used to investigate visuospatial attention, landmark and bisection tasks are indeed measuring different aspects of visuospatial attention (Harvey, Milner & Roberts, 2010). Moreover, performances in the landmark and in the greyscale tasks do not correlate (Heber et al. 2010) and are characterized by different ocular behaviors (Cavézian et al., 2012). To the best of our knowledge, no study has ever investigated whether ocular bisection would follow the typical left-to-right shift with increasing viewing distance. Similarly, empirical work on ocular bisections of illusion-inducing line segments is absent.

In the present study we therefore explored whether, in bisection task, the left-to-right shift with increasing viewing distance also applies to the processing of visual illusions. Participants were asked to manually bisect both physical lines and the Judd variant of the Müller-Lyer illusion, i.e., a line with two identical arrowheads at each end (Holding, 1970; Judd, 1899). Lines were projected on a large screen placed at three different spatial locations in the visual field (left, centre, right) and at three different viewing distances (60, 90, 120 cm) from the participants, who had to bisect the stimuli by moving a mouse with their dominant right hand.

First, by manipulating the spatial location of the lines, we investigate the hemispheric engagement in the transition from near to far space. Indeed, because of the contralateral nature of central visual projections, stimuli presented in the left hemispace are processed by the right hemisphere, and *vice versa* for those presented in the right hemispace (for a review see Jewell & McCourt, 2000). Accordingly, lines presented in the left hemispace induce more leftward bias than lines presented in the right hemispace (Luh, 1995; Reuter-Lorenz et al., 1990). Thus, we reasoned that, if the rightward shift of attention with increasing viewing distance is dependent on an asymmetrical hemispheric activation, the shift should be modulated by variations in azimuthal stimulus placement. More specifically, we predicted a greater rightward bias for lines presented to the right compared to the left hemispace, especially in far space.

Second, we reasoned that if the left-to-right bias with increasing viewing distance depends mainly on right parietal areas, being mostly activated in near space and progressively less at farther distances, the processing of the visual illusion should be independent from viewing distance. Various neuropsychological studies have demonstrated that right parietal lesions do not impact on visual illusory effects (Vallar & Daini, 2006). The posterior parietal cortex, which is part of the dorsal stream, is in fact mainly responsible for the coding of near space. On the contrary, the coding of information in far space is mainly governed by areas in the ventral stream (Bjoertomt et al., 2002). Notably, the ventral stream network plays a critical role also in the perception of visual illusions (Mancini, Bolognini, et al., 2011). Accordingly, no dissociation between near and far space should be observed in the bisection of Judd-illusion lines, while bisection of simple lines should reflect the dorsal/near space and the ventral/far space segregation.

Since left premotor and motor areas engaged during the right-hand manual bisection task (see Weiss et al., 2000, 2003) might represent a major confound in the supposed hemispheric asymmetries governing the near and far space encoding, we further explored the above mechanisms by means of an ocular bisection paradigm. Indeed, the left hemisphere activation in manual bisection tasks has been hypothesized to be partially responsible for the rightward shift of attention with increasing distance, especially when manual bisection is compared to performance in tasks devoid of manual action, such as the landmark task (Longo et al., 2015). Accordingly, in the present study the same participants were also required to bisect lines by fixating the centre of the stimuli (“ocular bisection”). Attention and eye movements share many functional anatomical areas in parietal, frontal and temporal cortex of the human brain (Corbetta et al., 1998). Critically, eye movements induce more bilateral activation and, therefore, engage each hemisphere to a similar extent (Corbetta, 1998; Corbetta et al., 1998; Nobre, Gitelman, Dias & Mesulam, 2000). Hence, ocular bisection allows us to directly test the hemispheric asymmetry hypothesis beyond near and far space dissociation. If the left-to-right bias with increasing distance is determined by a right hemisphere specialization for near space and by a progressive activation of left hemisphere areas at farther space, we would expect the same pattern in both ocular and manual bisections. Following the same rationale, we expect biases in the bisection of the Judd illusion to be independent from viewing distance.

2.2. METHODS

Participants

Twenty right-handed participants (11 women), aged between 22 and 36 (*M* age=26.4), took part in the study. Right handedness was established using the Edinburgh handedness test (Oldfield, 1971). None of the participants were on medication. Sighting eye dominance was determined for each participant using a variation of the Porta test (Porta, 1593; Crovitz and Zener, 1962; see Roth, Lora & Heilman, 2002). Participants were required to extend one arm and point their finger vertically with the corner of the room, with both eyes open. Participants had to close one eye, alternately, and to report which eye closure caused the largest alignment change (i.e., recorded as the dominant eye). Seventeen participants were classified as right eye dominant. Informed consent of all participants was obtained in written form after full explanation of the experimental procedure.

Eye tracking

Horizontal and vertical eye movements were recorded at 220 Hz with a head-mounted video-oculography (VOG) device (“EyeSeeCam”; Schneider, Dera, Bard, Bardins, Boening & Brand, 2005), consisting of swimming goggles with two mounted infrared cameras. A model of the eye rotation is used by the VOG system to derive the horizontal eye position from the pupil position recorded in the coordinate system of the cameras. Eye position was computed by asking subjects to look at a sequence of fixation points. We then fitted a linear function to the fixation position (in camera coordinates) to the sine of the target eccentricity. An additional offline calibration was performed to improve the accuracy at each viewing distance (60, 90 and 120 cm).

Stimuli and apparatus

Stimuli consisted of three white-line configurations: *a*) left-displaced Judd illusions (leftward outgoing/rightward ingoing fins), *b*) simple lines, and *c*) right-displaced Judd illusions (leftward ingoing/rightward outgoing fins) (see **Figure 2.1b**, **2.1c** and **2.1d**, respectively). Stimuli were displayed by a projector, mounted on the ceiling, on a large screen (220x220 cm) and were presented on a black background with constant luminance (see **Figure 2.1a**). Simple lines measuring 22° were displayed. The horizontal line of the Judd illusion was also 22°, whereas the arrows at the two ends were angled at 45° and measured 25% of the horizontal line. Participants had to perform manual and ocular bisection of the stimuli at three different distances (60, 90 and 120 cm) in separate sessions. The visual angle subtended by the lines was held constant across the different distances – i.e., 60 cm (24.24 cm), 90 cm (36.36 cm), 120 cm (48.48 cm). In each experimental block, stimuli could appear in three different horizontal positions: in the left, in the central and in the right hemispaces. In the left and right hemispaces, the real midpoint of the line was displaced -12° and +12° from the centre of the screen, respectively. The visual angle of the displacement was also held constant across the three different distances.

Participants performed the experimental blocks seated on a chair. The height of the chair was adjusted so that participants' eyes were aligned with the screen vertical midpoint (i.e., the vertical position of stimuli presentation). Head movements were restricted with an individually molded thermoplastic mask, in order to minimize movement artifact (Sinmed BV, Reeuwijk, The Netherlands). Matlab software (Mathworks, Natick, MA; release 2008b) was used for programming, presentation of stimuli, and timing operations.

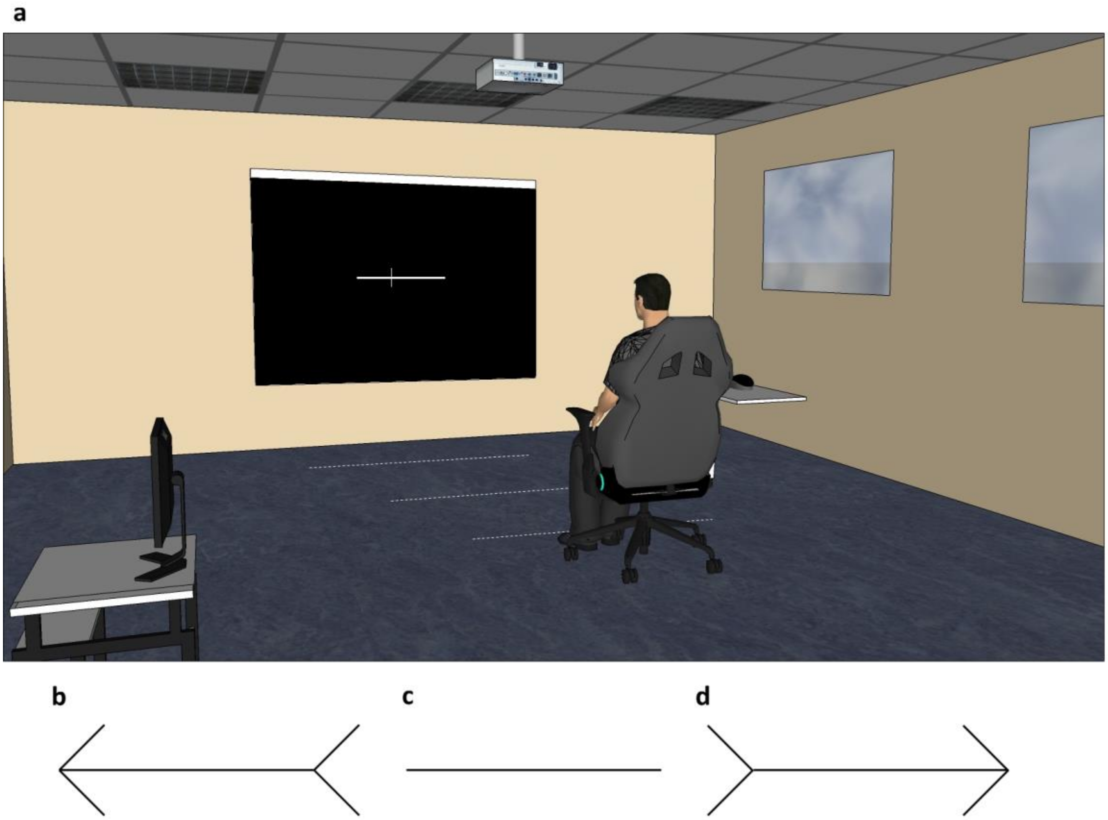

Figure 2.1. a) The experimental setup of the study: participants were seated on a chair, which could be positioned at three different distances (60, 90 and 120 cm), with their heads restricted with an individually molded thermoplastic mask (not shown). Participant had to perform a bisection task of stimuli projected on a large screen, by means of a mouse (manual bisection) or of their eyes (ocular bisection). b), c), d) The three types of stimulus configuration: left-displaced Judd illusions (b), simple lines (c) and right-displaced Judd illusions (d) to be bisected. Lines length measured 22°.

Procedure

Participants completed 2 tasks (one manual and one ocular bisection) at each viewing distance (60, 90 and 120 cm), for a total of six blocks. Order of distances and order of blocks within the same viewing distance were counterbalanced between participants.

In the manual bisection task, participants were instructed to indicate the line midpoint by using the mouse. Half of the trials began when the mouse cursor appearing at the leftmost end of the line, whereas the other half started with the mouse cursor appearing at the rightmost end (starting position). The mouse cursor was a 2° vertical white line, moving only along the horizontal axis and aligned perpendicularly to the stimulus. Participants indicated the line midpoint by clicking the mouse with their right hand.

In the ocular bisection task, participants were instructed to indicate the line midpoint by means of their gaze. Half of the trials began with a red dot appearing 5° below the leftmost end of the line, whereas the other half started with a dot appearing 5° below the rightmost end (starting position). The line appeared on the screen only if participants fixated the dot and it remained on the screen for 3 seconds. Participants were then allowed to scan the line in the first instant and subsequently to fixate its midpoint.

In each block (manual or ocular bisection at the three viewing distances) the combination of three types of stimulus configuration (left-displaced Judd illusions, simple lines, right-displaced Judd illusions) and of the three spatial locations (left, centre, right) generated nine possible types of stimuli. Each type of stimulus was presented six times, three in the left and three in the right starting positions, for a total of 54 trials. The different starting positions, however, did not constitute experimental manipulations, and were therefore not analyzed. For each participant and for each experimental block, a different random sequence was used.

2.3. RESULTS

The manual bisection score was computed as the mouse cursor position along the line in the instant when the participant clicked the mouse button. The ocular bisection score was computed as the median of the horizontal eye position in the last second of line presentation. Since different line lengths were used at the three distances, deviations from the veridical center were converted to signed percentage scores (positive if bias was to the right, negative if it was to the left). This was done by subtracting the true half-length of the line from the measured response distance of each trial from the left end of the line (in cm and visual angle for the manual and the ocular bisections, respectively), and then dividing this value by the true line length and multiplying the quotient by 100. Thus, two bias scores were obtained, one each for manual and ocular bisections.

Different analyses were computed for the manual bisection and the ocular bisection scores, on each stimulus configuration (left-displaced Judd illusions, simple lines, right-displaced Judd illusions). We used *t*-tests to compare averaged bias scores for each distance (60, 90, 120 cm) and for each spatial location (left, centre, right) against zero (i.e., the real midpoint value). A repeated measures analysis of variance (ANOVA) with distance (60, 90, 120 cm) and spatial location (left, centre, right condition) as within-subjects variables was also performed. Finally, Pearson correlation analyses were performed to assess the relationship between manual and ocular performance on each stimulus configuration.

Simple line

Manual bisection

First, a series of *t*-tests on the average of the manual bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant leftward bias (pseudoneglect) for lines presented in the left hemispace at 60 cm, whereas a trend was observed for lines presented centrally at 60 cm and in the left hemispace at 90 cm of distance. In the other conditions, the bias did not differ from zero (see **Table 2.1**).

A repeated measures ANOVA revealed a main effect of distance, $F(2, 38)=7.01$, $p<.005$, $\eta^2_p=.27$. Post-hoc comparisons[1] showed that lines presented at 60 cm ($M=-.46$, $SD=1.16$) were bisected significantly more leftward than lines presented at 90 ($M=-.17$, $SD=1.06$; $p<.05$) and 120 cm ($M=.18$, $SD=1.17$; $p<.01$). Furthermore, a trend with a more leftward bias for lines presented at 90 cm than those presented at 120 cm was found ($p=.064$). The main effect of spatial location was also significant $F(2, 38)=10.16$, $p<.001$, $\eta^2_p=.35$. Post-hoc comparisons showed that lines presented in the left hemispace ($M=-.44$, $SD=1.11$) were bisected significantly more leftward than lines presented centrally ($M=-.18$, $SD=1.08$; $p<.05$) and in the right hemispace ($M=.17$, $SD=1.21$; $p<.005$). Furthermore, lines presented centrally were bisected more leftward than those presented in the right hemispace ($p<.01$). Finally, the interaction distance by spatial location was not significant, $F(4, 76)<1$, $p=.89$ (see **Figure 2.2a**).

Ocular bisection

First, a series of *t*-tests on the average of the ocular bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant leftward bias, i.e., indicating the presence of pseudoneglect, for lines presented both in the left hemispace and centrally at 60 cm of viewing distance. Furthermore, a rightward bias was found for lines presented in the right hemispace at 90 cm. In the other conditions, the bias did not differ from zero (see **Table 2.1**).

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[1] Bonferroni correction was applied to all multiple comparisons.

A repeated measures ANOVA revealed a main effect of distance, *F*(2, 38)=4.68, *p*<.05, η^2_p=.19. Post-hoc comparisons showed that lines presented at 60 cm (*M* =-1.69, *SD*=2.66) were bisected significantly more leftward than lines presented at 120 cm (*M*=.9, *SD*=2.81; *p*<.001), whereas a leftward trend was observed compared to lines presented at 90 cm (*M*=.69, *SD*=4.45; *p*=.063). No difference was found between lines bisected at 90 and 120 cm (*p*=.84). The main effect of spatial location was also significant *F*(2, 38)=17.06, *p*<.001, η^2_p=.47. Post-hoc comparisons showed that lines presented in the left hemispace (*M*=-.88, *SD*=3.19) were bisected significantly more leftward than lines presented centrally (*M* =-.12, *SD*=4.03; *p*<.05) and in the right hemispace (*M*=.89, *SD*=3.32; *p* < .001). Furthermore, lines presented centrally were bisected more leftward than those presented in the right hemispace (*p*<.005). Finally, the interaction distance by spatial location was not significant, *F*(4, 76)<1, *p*=.42 (see **Figure 2.2b**).

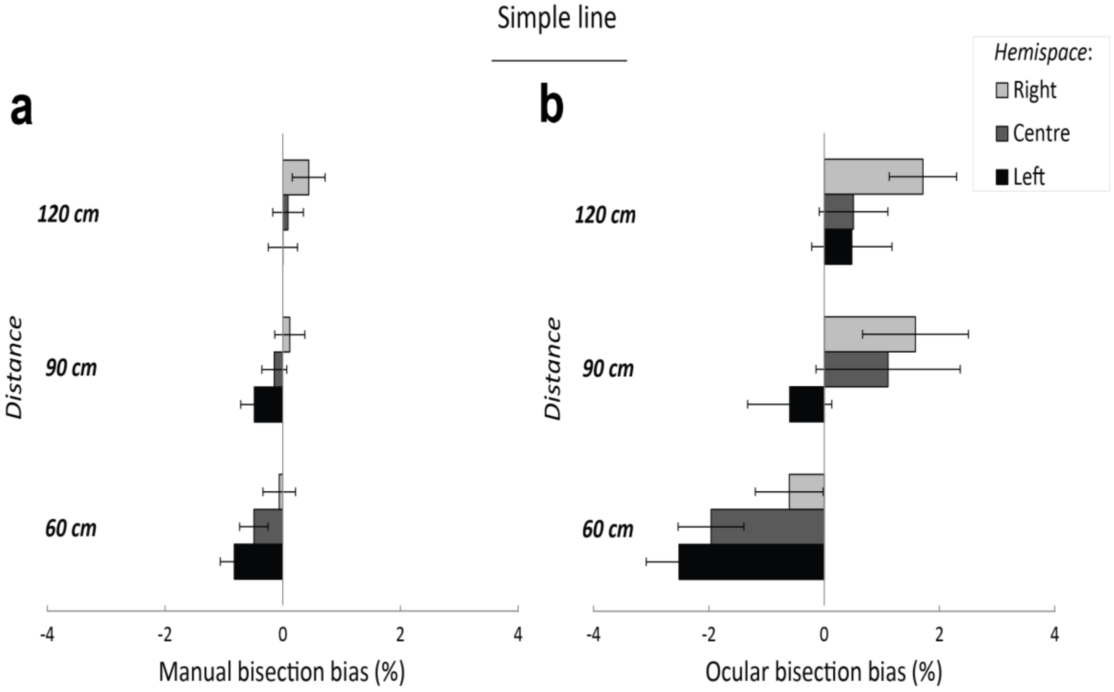

Figure 2.2. Mean percent error (±SEM) in manual (a) and ocular (b) bisection of simple lines, by distance (60, 90 and 120 cm) and by spatial location (left, centre, right). Negative/positive score indicates leftward/rightward bias.

Table 2.1. *T*-test results (against the value of the real midpoint of the line) in the manual and in the ocular bisection of the simple lines, presented by spatial location (left, centre, right) and by viewing distance (60, 90, 120 cm).

	Manual bisection			**Ocular bisection**		
Hemispace	**Left**	**Centre**	**Right**	**Left**	**Centre**	**Right**
Distance						
60 cm	*t*=-3.45 *p*<.005	*t*=-2.03 *p*=.057	*t*=-.22 *p*=.83	*t*=-4.41 *p*<.001	*t*=-3.44 *p*<.005	*t*=-1.03 *p*=.32
90 cm	*t*=-2.09 *p*=.051	*t*=-.68 *p*=.51	*t*=.47 *p*=.65	*t*=-.82 *p*=.42	*t*=.89 *p*=.39	*t*=1.73 p=.1
120 cm	*t*=.01 *p*=.99	*t*=.35 *p*=.73	*t*=1.59 *p*=.13	*t*=.69 *p*=.5	*t*=.86 *p*=.4	*t*=2.94 *p*<.01

Relationship between manual and ocular bisection

No correlation was found between manual and ocular bias scores at 60 cm [left hemispace: *r*(20)=.29, *p*=.2; centre: *r*(20)=-.14, *p*=.55; right hemispace: *r*(20)=-.19, *p*=.43], 90 cm [left hemispace: *r*(20)=.14, *p*=.56; centre: *r*(20)=.37, *p*=.11; right hemispace: *r*(20)=.32, *p*=.18] and 120 cm [left hemispace: *r*(20)=.33, *p*=.15; centre: *r*(20)=.31, *p*=.18; right hemispace: *r*(20)=.26, *p*=.26].

Left-displaced Judd illusion

Manual bisection

First, a series of *t*-tests on the average of the manual bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant rightward bias in all conditions, indicating that subjective midpoint was shifted towards the tail end, consistent with the effect of the Judd illusion (see **Table 2.2**).

A repeated measures ANOVA revealed neither a main effect of distance, *F*(2, 38)=1.29, *p*=.29, nor of spatial location, *F*(2, 38)<1, *p*=.49. No significant interaction emerged, *F*(4, 76)<1, *p*=.85 (see **Figure 2.3a**).

Ocular bisection

First, a series of *t*-tests on the average of the ocular bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant rightward bias in all conditions, indicating that subjective midpoint was shifted towards the tail end, consistent with the effect of the Judd illusion (see **Table 2.2**).

A repeated measures ANOVA revealed a main effect of spatial location, *F*(2, 38)=9.96, *p*<.001, η^2_p=.34. Post-hoc comparisons showed that lines presented in the left hemispace (*M*=3.37, *SD*=3.92) were bisected significantly more leftward than lines presented centrally (*M*=4.13, *SD*=4.15; *p*<.01) or in the right hemispace (*M*=4.92, *SD*=3.98; *p*<.005). Furthermore, lines presented centrally were bisected more leftward than those presented in the right hemispace (*p*<.05). The main effect of distance, *F*(2, 38)=1.51, *p*=.23, and the interaction distance by spatial location, *F*(4, 76)<1, *p*=.57, were both not significant (see **Figure 2.3b**).

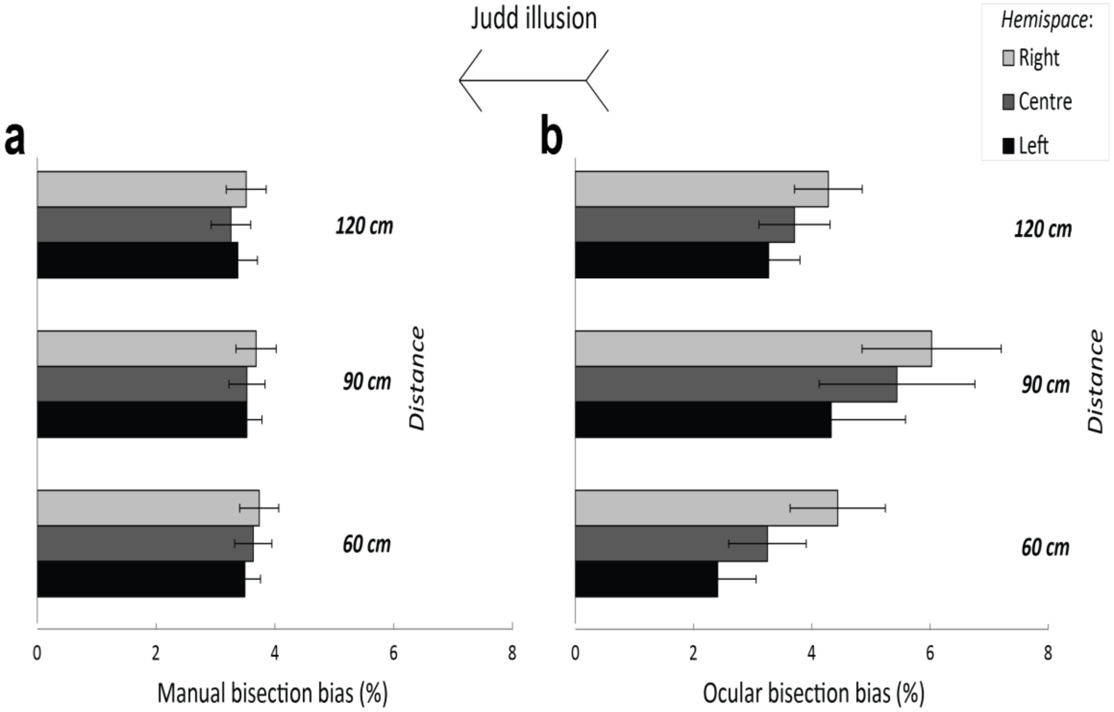

Figure 2.3. Mean percent error (±SEM) in manual (a) and ocular (b) bisection of left-displaced Judd illusions, by distance (60, 90 and 120 cm) and by spatial location (left, centre, right). Negative/positive score indicates leftward/rightward bias.

Table 2.2. *T*-test results (against the value of the real midpoint of the line) in the manual and in the ocular bisection of the left-displaced Judd illusions, presented by spatial location (left, centre, right) and by viewing distance (60, 90, 120 cm).

	Manual bisection			**Ocular bisection**		
Hemispace	**Left**	**Centre**	**Right**	**Left**	**Centre**	**Right**
Distance						
60 cm	*t*=13.26	*t*=11.62	*t*=11.37	*t*=3.7	*t*=4.97	*t*=5.52
	p <.001	*p*<.001	*p*<.001	*p*<.005	*p*<.001	*p*<.001
90 cm	*t*=13.89	*t*=11.63	*t*=10.87	*t*=3.44	*t*=4.13	*t*=5.12
	p<.001	*p*<.001	*p*<.001	*p*<.005	*p*<.002	*p*<.001
120 cm	*t*=10.23	*t*=9.78	*t*=10.43	*t*=6.18	*t*=6.16	*t*=7.47
	p<.001	*p*<.001	*p*<.001	*p*<.001	*p*<.001	*p*<.001

Relationship between manual and ocular bisection

No correlation was found between manual and ocular bias scores at 60 cm [left hemispace: *r*(20)=.1, *p*=.68; centre: *r*(20)=-.2, *p*=.39; right hemispace: *r*(20)=.28, *p*=.24] and 90 cm [left hemispace: *r*(20)=.35, *p*=.13; centre: *r*(20)=.34, *p*=.15; right hemispace: *r*(20)=.17, *p*=.47]. On the other hand, at 120 cm a positive correlation [*r*(20)=.54, *p*<.05] emerged in the left hemispace and a trend [*r*(20)=.42, *p*=.06] in the centre, whereas no relationship was found in the right hemispace [*r*(20)=.38, *p*=.1].

Right-displaced Judd illusion

Manual bisection

First, a series of *t*-tests on the average of the manual bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant leftward bias in all conditions, indicating that subjective midpoint was shifted towards the tail end, consistent with the effect of the Judd illusion (see **Table 2.3**).

A repeated measures ANOVA revealed neither a main effect of distance, *F*(2, 38)=1.53, *p*=.23, nor of spatial location, *F*(2, 38)=2.62, *p*=.09, nor a significant interaction distance by spatial location, *F*(4, 76)<1, *p*=.98 (see **Figure 2.4a**).

Ocular bisection

First, a series of *t*-tests on the average of the ocular bisection scores against zero (i.e., the real midpoint value) were performed. Results showed a significant rightward bias in all conditions, indicating that subjective midpoint was shifted towards the tail end, consistent with the effect of the Judd illusion (see **Table 2.3**).

A repeated measures ANOVA revealed a main effect of spatial location, $F(2, 38)=4.65$, $p<.05$, $\eta^2_p=.19$. Post-hoc comparisons showed that lines presented in the left hemispace ($M=-4.04$, $SD=4.58$) were bisected more leftward than lines presented in the right hemispace ($M=-3.86$, $SD=5.13$; $p<.05$), but not of those presented centrally ($M=-2.73$, $SD=4.49$; $p=.65$). Furthermore, lines presented centrally were bisected more leftward than those presented in the right hemispace ($p<.05$). The main effect of distance, $F(2, 38)=1.66$, $p=.2$, and the interaction distance by spatial location, $F(4, 76)<1$, $p=.45$, were both not significant (see **Figure 2.4b**).

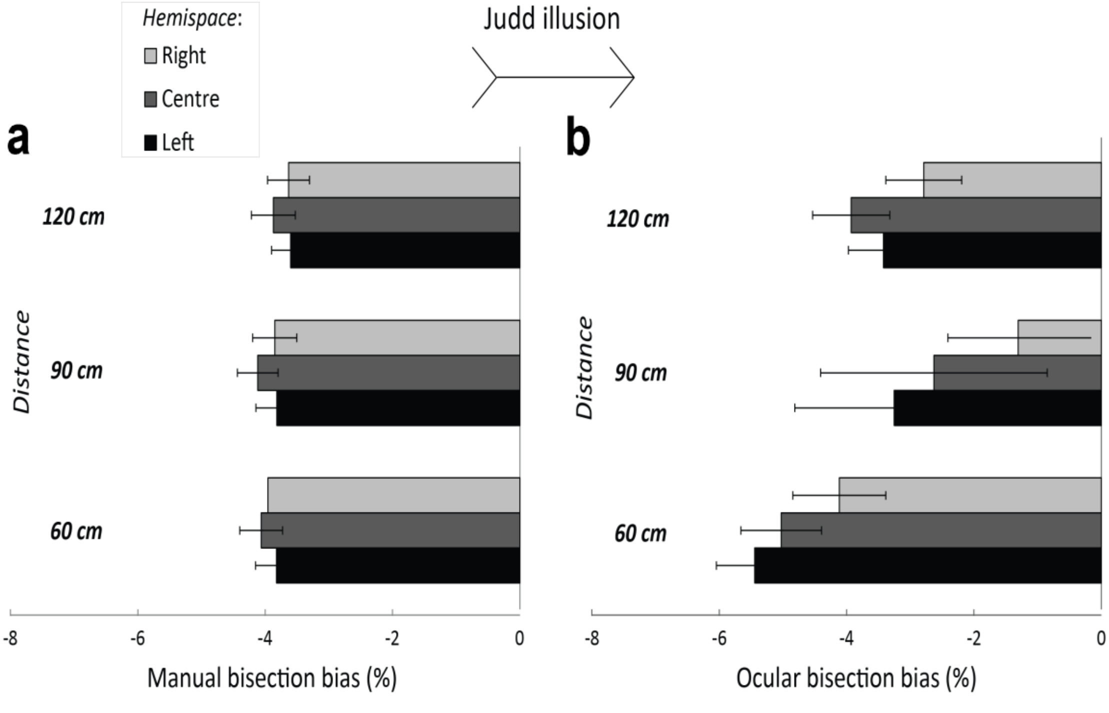

Figure 2.4. Mean percent error (±SEM) in manual (a) and ocular (b) bisection of right-displaced Judd illusions, by distance (60, 90 and 120 cm) and spatial location (left, centre, right). Negative/positive score indicates leftward/rightward bias.

Table 2.3. *T*-test results (against the value of the real midpoint of the line) in the manual and in the ocular bisection of the right-displaced Judd illusions, presented by spatial location (left, centre, right) and by viewing distance (60, 90, 120 cm).

	Manual bisection			**Ocular bisection**		
Hemispace	**Left**	**Centre**	**Right**	**Left**	**Centre**	**Right**
Distance						
60 cm	*t*=-11.67 *p*<.001	*t*=-12.05 *p*<.001	*t*=-12.2 *p*<.001	*t*=-9.07 *p*<.001	*t*=-7.94 *p*<.001	*t*=-5.63 *p*<.001
90 cm	*t*=-11.63 *p*<.001	*t*=-12.88 *p*<.001	*t*=-11.09 *p*<.001	*t*=-2.08 *p*=.05	*t*=-1.48 *p*=.16	*t*=-.91 *p*=.37
120 cm	*t*=-12.03 *p*<.001	*t*=-11.21 *p*<.001	*t*=-11.03 *p*<.001	*t*=-6.22 *p*<.001	*t*=-6.48 *p*<.001	*t*=-4.68 *p*<.001

Relationship between manual and ocular bisection

No correlation was found between manual and ocular bias scores at 60 cm [left hemispace: *r*(20)=.08, *p*=.75; centre: *r*(20)=.39, *p*=.09; right hemispace: *r*(20)=-.17, *p*=.48], 90 cm [left hemispace: *r*(20)=.16, *p*=.48; centre: *r*(20)=.23, *p*=.34; right hemispace: *r*(20)=.42, *p*=.06] and 120 cm [left hemispace: *r*(20)=.22, *p*=.35; centre: *r*(20)=.37, *p*=.11; right hemispace: *r*(20)=.33, *p*=.15].

2.4. DISCUSSION

The present study investigated the processing of near and far space, contrasting for the first time visuospatial asymmetries and visual illusory effects in both a manual and an ocular bisection task. In accordance with the literature, we found that the bisection of simple lines was modulated by viewing distance (Bjoertomt et al., 2002; Gamberini et al., 2008; Heber et al., 2010; McCourt & Garlinghouse, 2000; Longo & Lourenco, 2006; Varnava et al., 2002). A recent study suggested that the right-to-left shift of the bisection bias with increasing viewing distance is dependent on an hemispheric imbalance in processing near and far space, specifically on a relative specialization of the right hemisphere for orienting attention in near space (Longo et al, 2015). We replicated such a preferred near-space processing by the right hemisphere in a simple line bisection task. Importantly, we ruled out possible confounds played by unilateral brain activation due to hand motor activity (Weiss et al., 2000, 2003), since the same pattern of results was found in an ocular line bisection paradigm. Interestingly, no comparable interaction between lateral attention and stimulus distance was observed when the perception of line length was distorted by flanked arrow heads (the Judd illusion). The dissociation between the processing of pure visuospatial information and that of a visual illusion provides novel evidence for the dorsal/near space and the ventral/far space segregation.

We will discuss the key findings of the present study in turn, starting with the differential hemispheric processing of near and far space, which will lead us to address the segregation between dorsal and ventral streams, and finally to discuss similarities and differences between manual and ocular bisection behavior.

2.4.1 Hemispheric imbalance for near and far space processing

A leading model of visuospatial attention, known as activation-orientation account, proposes that attention is biased contralaterally toward the most activated cerebral hemisphere, a tendency more pronounced in the left hemisphere (Kinsbourne, 1987; Loftus & Nicholls, 2012; Reuter-Lorenz et al., 1990). In line with this account, the leftward bias exhibited by the general population has been shown to be driven by the preferential activation of the right PPC during visuospatial tasks (Fink et al., 2002; Foxe et al., 2003; Göbel et al., 2006). More recently, however, Longo et al. (2015; see also Longo & Lourenco, 2006) found that the right parietal cortex primacy for processing visuospatial information might be limited to near space. When stimuli are presented at farther distances, indeed, the right hemisphere becomes progressively less activated (Longo et al., 2015).

The present study provides novel evidence for Longo et al.'s hypothesis (2015). First, we replicated the left-to-right shift in bisection bias with increasing distance (Gamberini et al., 2008; Longo & Lourenco, 2006; Varnava et al., 2002). Second, this shift was reported also for eye movements. Since left premotor and motor areas engaged during the right-hand manual bisection task (Weiss et al., 2000; 2003) might have represented a major confound in the supposed hemispheric asymmetries (see for a discussion also Longo et al., 2015), results from ocular bisection clearly demonstrate that the shift is mainly attentional. Third, we found that the bisection bias was modulated by variations in azimuthal line placement in both manual and ocular bisection. Pseudoneglect was indeed maximized at the nearest distance, but critically the largest leftward deviation was found when lines were presented in the left hemispace. Hence, the right hemisphere baseline tendency for processing far space was further strengthened by activation induced by contralateral stimulus presentation. This indicates that asymmetries responsible for the allocation of attention in near and far space interact with asymmetries imposed by azimuthal stimulus placement and, more generally, suggests that our brain computes online the metrics of the surrounding space by integrating the multiple coordinates of the spatial reference frames (i.e., in our case, depth and visual laterality).

Overall, our findings are in line with Longo et al.'s interpretation and speak in favor of an hemispheric unbalance for processing information at different distances. However, the preferential activation of the right occipito-parietal cortex for processing information close to the body might represent only one mechanism underlying the near/far space distinction. Indeed, a revised version of the activation-orientation model proposes that pseudoneglect may not solely originate from unilateral hemispheric unbalance, but also from a neural connectivity asymmetry between cerebral hemispheres. In particular, Siman-Tov et al. (2007) suggested that, along with the neural connectivity advantage within the right hemisphere for visuospatial attention (see Thiebaut de Schotten et al., 2011; see also Vallar et al., 2014), there is an asymmetry in the strength of connections between bilateral IPS, with preference for right-to-left connections. These two mechanisms would determine the left visual field advantage observed in healthy individuals. Hence, it is possible that the fast right-to-left inter-hemispheric conduction, partially responsible for the pseudoneglect, might be more accentuated in near than in far space.

2.4.2 Segregation between dorsal and ventral stream areas

Several studies have linked visuospatial performance to the dorsal visuomotor processing stream and performance in far space to the ventral visuoperceptual stream (Weiss et al., 2000; 2003). In two neuroimaging studies, Weiss et al. (Weiss et al., 2000; 2003) found a preferential activation of the parietal and premotor cortex for tasks performed in near space, and of the ventral occipital and medial temporal cortex for those performed in far space, a pattern of results replicated also in TMS studies (Bjoertomt et al., 2002; Lane, Ball Smith, Schenk & Ellison, 2013). Indeed, the dorsal stream would be dedicated to objects manipulation in (near) space, while the ventral stream would be mainly dedicated to visual perception (Milner & Goodale, 1995). A main, though controversial, lines of research investigating the extent of the dorsal/ventral stream segregation focused on motor responses to visual illusions (see Bruno, Bernardis & Gentilucci, 2008). In particular, studies using the bisection paradigm with variants of the Müller-Lyer illusion (Mancini, Bricolo et al., 2011; Mancini, Bolognini et al., 2011) suggested a preferential involvement of the ventral visual stream in visual illusions (see also Weidner et al., 2006; 2009).

On these grounds, we reasoned that if the near/dorsal and far/ventral segregation accounts for the rightward shift of bisection bias in simple line bisection with increasing distance, viewing distance should not modulate visual illusory effects. Results from both manual and ocular bisection of the Judd illusion indicated that this was likely the case. Indeed, the bias was similar in near and far space, thus suggesting that processing of visual illusions is independent from the near/dorsal and far/ventral segregation. This finding adds to previous neuropsychological evidence, indicating that visual illusory effects are preserved by “real” (for a review see Vallar & Daini, 2006) or “virtual” (Mancini et al., 2011) lesions in the right parietal cortex. Therefore, the reported dissociation provides novel evidence favouring the specificity of the dorsal stream for directing visuospatial attention in near space. More generally, these results support the view that different mechanisms subserve the processing of visual illusion and visuospatial information, respectively.

2.4.3 Differences and similarities between manual and ocular bisection

Scattered evidence has explored whether eyes and hands behave similarly or differently in visuospatial tasks (for a discussion see Thomas et al., 2014). Diverging results have been reported across studies, though the use of various experimental manipulations makes them barely comparable. Quite surprisingly, in some studies eye movements were found to be biased slightly to the right of the objective centre, whereas manual bisection bias was reported to the left (Elias et al. 2005; Leonards et al., 2013; but see Cavézian et al. 2012, and Hurwitz et al., 2011, for exceptions). This pattern has been explained by the fact that gazing to the right would leave a larger portion of the line in the left visual field (Leonards et al., 2013; Thomas et al. 2012). In the present study, however, we found a significant leftward deviation in near space for centrally presented lines, in the ocular bisection. Yet, while in the present study lines subtended a visual angle of 22°, in the Leonards et al.'s study a shorter line length was used (9° of visual angle; Leonards et al., 2013). Indeed, we notice that the magnitude of the bias usually increases with line length (Jewell and McCourt, 2000). Hence, the rightward ocular bias found in previous studies might turn out to slightly shift to the left when line length increases, as in the present study. Third, it is worth noting that in previous studies (Elias et al. 2005; Leonards et al., 2013) right-handed participants indicated the point of their final fixation by pressing a button, while here no manual response was required in the ocular bisection. This manual movement, inducing activation of the left hemisphere, might have therefore influenced such findings. On the contrary, our ocular results replicate the leftward bias in near space found by means of a similar paradigm (i.e., ocular bisection by fixation) in the study by Cavézian et al. (2012). Furthermore, and consistent with an ocular rightward bias for far space, a previous study found a rightward bias in eye fixation during navigation (Robertson, Forte & Nicholls, 2015).

In sum, our study indicated that eyes and hands were both affected by viewing distance and by the spatial location of simple lines. Thus, attentional resources were similarly distributed in the surrounding space, possibly driven by an asymmetrical activation of cerebral hemispheres. Importantly, whereas the biases were similar for manual and ocular bisection, the two performances were not correlated (Hurwitz et al., 2011; Leonards et al., 2013; Thomas et al., 2012; 2014). This finding adds to previous evidence indicating that manual and oculomotor behaviors are driven by different mechanisms that subserve spatial processing. Our results suggest, however, that manual and oculomotor processes are independent, rather than complementary, i.e., bias opposite for manual and ocular bisection (Leonards et al., 2013).

Visual illusory effects have been also investigated by means of eye movements. Ocular behavior is usually widely affected by the Müller-Lyer illusion, as assessed by repeated saccades from one endpoint to the other of the segment (Bruno, Knox & de Grave, 2010). However, no study has so far investigated whether illusory effects extend to the ocular bisection. Our results showed that the visual illusion clearly affected eye movements. Furthermore, in both the manual and the ocular bisection, viewing distance had no effect whatsoever on the performance, thus reflecting similar mechanisms mediating processing of the visual illusion in near and far space.

READING DIRECTION SHIFTS VISUOSPATIAL ATTENTION:

An interactive account of attentional biases

Chapter adapted from:
Rinaldi, L., Di Luca, S., Henik, A. & Girelli, L. (2014). Reading direction shifts visuo-spatial attention: an Interactive Account of attentional biases. *Acta Psychologica*, *151*, 98-105.

3.1. INTRODUCTION

Neurobiological determinants have been commonly offered to account for the spatial biases in human performance. Right hemisphere dominance for spatial cognition (e.g., Bradshaw et al., 1987; Kinsbourne, 1970) along with the asymmetry in the neural mechanisms involved in attention (Nicholls & Roberts, 2002) have been suggested to underlie such biases. However, there is increasing evidence for cultural modulation of visuospatial performance (see **Chapter 1**). The present study: *1)* investigated the role of cultural factors in visuospatial exploration, by comparing three groups with different reading habits, and *2)* manipulated language (e.g., English and Hebrew letters) to examine effects of context.

A prototypical example of asymmetries in spatial performance is represented by the slight leftward bias, known as pseudoneglect (Bowers & Heilman, 1980), generally shown by healthy participants in bisection tasks in near space (see **Chapter 2**), in both the visual and haptic modality (for a review, see Jewell & McCourt, 2000), resulting from the overestimation of the left side of space. This pattern mimics the rightward bias characterizing bisection performance of neglect patients. Neglect patients show difficulties in reporting, orienting, and responding to stimuli in the contralesional hemispace more frequently after damage to the right than to the left brain hemisphere (Halligan et al., 2003; Heilman et al., 1993). Both behavioral and neuropsychological evidence, thus, converge in pointing to an imbalanced hemispheric activation in spatial tasks, partially resulting from the predominant role of the right fronto-parietal network in visuospatial and attentional functions (Bartolomeo, Thiebaut de Schotten & Chica, 2012; Corbetta & Shulman, 2011). In support of a pure neurobiological account of spatial asymmetries, pseudoneglect-like effects have been reported in non-human species such as in the pecking activity of birds (Diekamp, Regolin, et al., 2005) and in the bisection performance of chickens (Diekamp, Manns, et al., 2005; Regolin, 2006), suggesting a common evolutionary lateralization of spatial attention.

On the other hand, over the years, it has been found that cultural practices, such as reading habits, broadly influence the cognitive system, inducing spatial biases at both perceptual and representational levels (see **Chapter 1**). Accordingly, evidence for the cultural shaping of visuospatial performance is not lacking. Chokron and Imbert (1993), indeed, showed that Hebrew readers bisected lines to the right of the true center, while native French readers bisected lines to the left of the center (see also, Kazandjian et al., 2010). Similar patterns have been detected also in preschoolers, where directional asymmetries might originate by observational learning and by trained eye scanning habits in visual-perception, indirectly related to reading habits (Chokron & De Agostini, 1995). Language-dependent effects have been reported also in line extension (Chokron et al., 1997) and line partition (Zivotofsky, 2004) tasks, although their consistency has been challenged by controversial results (Nicholls & Roberts, 2002). Importantly, previous studies focusing on reading direction effects involved mainly Israeli participants who can hardly be considered monolingual, due to their experience with left-to-right material (i.e., English learning) throughout their education (Chokron et al., 2011). Overall, evidence for a culturally based or a neurobiologically based account of visuospatial asymmetries is both available and debatable.

The present study used a classic line bisection task and a computerized cancellation task to examine the role of reading habits in perceptual asymmetries. Cancellation tasks have long been used in the neurological assessment of visuospatial functions and selective attention, both in healthy subjects and in neuropsychological patients (Parton, Malhotra & Husain, 2004). Recent investigations on the cancellation task suggest a highly organized exploration of the visual scene (Manly et al., 2009; Mark et al., 2004; Woods & Mark, 2007). Interestingly, the searching strategy has been shown to change over written language acquisition (Brucki & Nitrini, 2008) and over the school years (Woods et al., 2013), shifting the distribution of visuospatial attention asymmetrically. To the best of our knowledge, only one study investigated cancellation performance in right-to-left readers and reported no spatial asymmetry in the distribution of omissions (Geldmacher & Alahj, 1999). However, because language competence was not systematically assessed and control reading groups were not considered, these results remain suggestive.

The classic paper-and-pencil version of the cancellation task presents limitations that have been overcome by the recent development of computer-assisted evaluation, which is more sensitive to attentional mechanisms and visuospatial performance in healthy adults (Di Luca, Pesenti, Vallar & Girelli, 2013), neglect patients (Rabuffetti et al., 2012) as well as in school-children (Wang, Huang & Huang, 2006). Specifically, it allows for a variety of indexes to analyze behaviors that are hardly registered in the paper-and-pencil cancellation test. Additionally, the computerized techniques are less time-consuming and labor-intensive than other procedures as, for example, the video recording method (Manly et al., 2009; Mark et al., 2004).

In the present study, we used a computerized version of the line bisection task and two versions of the star cancellation task (Wilson et al., 1988), performed with the help of a graphics tablet. This equipment allows us to record both visuospatial and visuomotor parameters of performance. Participants were monolingual left-to-right, monolingual right-to-left and bilingual readers (i.e., reading in both directions). The star cancellation task is composed of verbal and non-verbal stimuli. It comprises 56 small stars (targets) pseudo-randomly distributed among distractors (large stars, letters and words). Expanding on the original star cancellation task (Wilson et al., 1988), a new version with Hebrew letters and words as distractors was adopted. Participants performed a computerized line bisection task that constrained visuospatial processing by minimizing the impact of visuomotor performance.

Overall, the present study allowed us to contrast two alternative accounts of the asymmetries in visuospatial performance. According to *a Laterality account* (or *Activation orientation account;* Kinsbourne, 1970; Reuter-Lorenz, Kinsbourne & Moscovitch, 1990), we should expect no group difference in the indexes associated to the visual search due to the right hemisphere dominance in task execution; thus, a leftward bias (associated to a rightward-oriented visual search) would emerge regardless of reading habit. Moreover, biomechanical factors related to the preferential direction of hand movements (i.e., outward vs. inward hand movements) might contribute to making the leftward bias in right-handed subjects more consistent (Dreman, 1974). According to an *Interactive account,* neurobiological determinants of visuospatial asymmetries are critically modulated by directional oculomotor routines associated to reading and writing exploration. Thus, we do not expect opposite directional readers to show mirrored patterns, that is, a leftward bias in left-to-right readers and a similar rightward bias in right-to-left readers. Instead, the rightward deviation should be attenuated in right-to-left readers compared with left-to-right readers. Bidirectional readers would show an intermediate, more symmetrical exploration of visual space. Additionally, this group might be sensitive to the manipulation of the alphabetic context related to the Hebrew or English distractors.

3.2. METHODS

Participants

A total of 67 participants took part in the study: 23 Italian students (9 males), average age 21.7 ± 1.8 years, from the University of Milano-Bicocca (Italy); 21 Israeli Orthodox Jewish participants (15 males), average age 20.7 ± 2.5 years, who were enrolled in religious colleges for Jewish studies; and 23 bilingual Israeli subjects (5 males), with an average age of 25.7 ± 2.7 years, from the Ben-Gurion University of the Negev (Israel). The bilingual right-to-left reading participants (i.e., Bi group) were native-born Israelis with Hebrew as their mother tongue, and with good English skills; they were all familiar with a left-to-right language, and had started to learn English from the fifth grade of primary school. Italian (i.e., MoLR group) and Israeli Orthodox Jewish (i.e., MoRL group) subjects were all monolinguals and therefore constituted a monodirectional group. We assessed the English literacy of the latter group with a letter and single-words reading and comprehension test; only participants with no knowledge of English were included in the study (i.e., those who failed to read simple letters and words). Additionally, no subject of the MoRL group reported being familiar with any other left-to-right languages and no one in the MoLR group reported familiarity with a Semitic language. The average age differed significantly in the three groups, $F(2, 64)=29.63$, $p<.001$, $\eta^2_p=.48$, with the Bi group significantly older than both the MoLR ($p<.001$) and the MoRL group ($p < .001$). This difference was due to mandatory military service, which delayed the beginning of university courses for most non-Orthodox Israelis students for a minimum of two years. However, all groups were comparable in terms of years of education.

All participants had normal or corrected-to-normal visual acuity and were naïve with respect to the experimental hypotheses. Five participants (i.e., 1 from the Bi group and 2 from each monolingual group) were excluded a priori from the analyses due to technical problems. Manual laterality was assessed by using the Edinburgh Inventory (Oldfield, 1971): the Bi group and the MoLR group were equal in terms of participants’ handedness (in each group, 19 participants were classified as right-handed, 3 as left-handed and 1 as not completely lateralized). In the MoRL group 16 subjects were right-handed and 5 left-handed. Subjects were presented first with the line bisection task and then with the two cancellation tasks, in a counterbalanced order across subjects.

Cancellation task

Apparatus

The experiment was run on a Wacom Intuos 3 graphics tablet (Model PTZ-631W, 271 x 158.8 mm) with 1,024 levels of pressure (resolution: 5,080 dpi; sample-rate: 200 points/sec.) and a Intuos3 Ink Pen. The Ink Pen was pressure sensitive and captured every mark written on the paper by means of an adaptation of the VB Digital Draw software. Each matrix was presented individually on a paper placed on the surface of the graphics tablet. Responses (number of targets detected), vector coordinates (*x* and *y* pen down coordinates per ms) and response time (for each point) were collected throughout the experiment from the graphic tablet by interaction of the Ink Pen. Coordinates of all marks were identified and distinguished from relative movements (i.e., between targets) by a standard positive/absent pressure measure.

Tasks and stimuli

The original star cancellation task (Wilson et al., 1988) includes 45 capital letters (sometimes composed of short words) displayed in 23 different positions and printed among small and large stars, all randomly distributed. Targets are represented by small stars (see **Figure 3.1a**). As shown in **Figure 3.1b**, our adaptation consisted of replacing English letters and words with correspondent Hebrew letters and words. Specifically, the English and Hebrew star cancellation tasks were composed of 56 targets (small stars), and 75 distractors (52 large stars and 23 letters/words). In the “English” matrix subjects were shown 13 letters (e.g., C, G, E, etc.) and 10 words (e.g., DAY, TEN, etc.); the same number of distractors characterized the “Hebrew” matrix (see Figure 1b). The two cancellation matrices were printed on standard white sheets of paper (270 mm length x 158 mm height), attached in a fixed position on the surface of the graphics tablet that recorded participants’ performance.

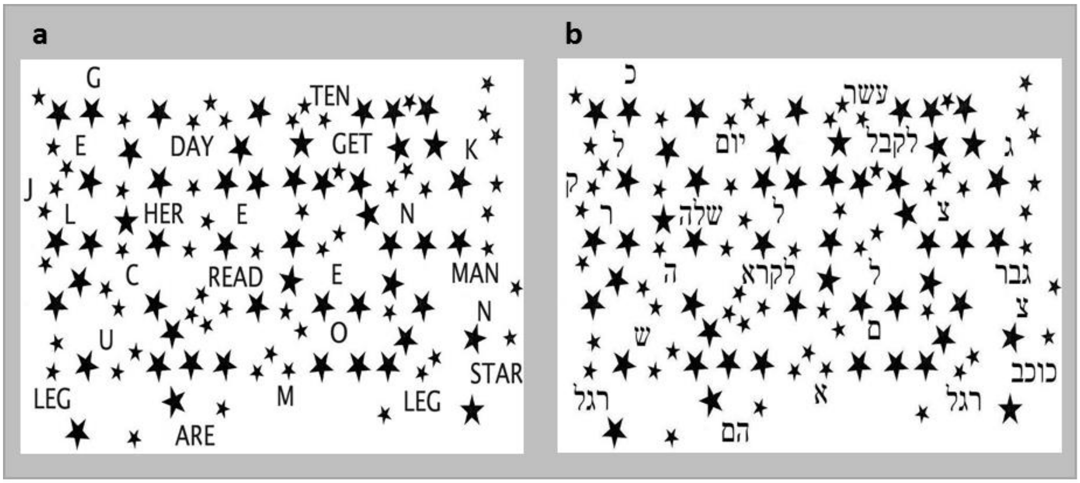

Figure 3.1. Tasks and stimuli used in this study. a) English matrix (Wilson et al., 1988), with English letters and words as distracters. b) Our Hebrew adaptation of the matrix, with Hebrew letters and words as distracters. The aim of the task was to cancel out all the targets (i.e., the small stars in the matrix) as rapidly and as accurately as possible. The experiment was run on a Wacom Intuos 3 graphics tablet.

Procedure

The two cancellation tasks (i.e., English and Hebrew) were administered in a counterbalanced order across participants. Each task was preceded by specific instructions indicating which target to be marked (i.e., the small stars) and specifying to mark all the targets on the paper as rapidly and as accurately as possible, with a line stroke of the Ink Pen.

Each participant was seated with the mid-sagittal plane of the trunk of his/her body transversally aligned to the center of the graphics tablet (which was placed on a desk in front of the participant). Each matrix was presented individually. Participants were informed of the time limit and after 30 seconds[1] the task was interrupted. Before the experimental test, participants were shown how to correctly perform the cancellation task on a practice matrix.

Data analysis

Cancellation performance was analyzed by six indexes. The time for completion as well as number and location of all marked targets were recorded for each cancellation. Coordinates of every mark (determined by the pen's pressure), and every movement (between targets) and corresponding relative response time on the x and y axes were computed: thus, data analyses are differently reported on the horizontal and on the vertical axes. Cultural effects are expected on the horizontal axis, with the vertical axis serving as the control condition. All data analyses were performed using Matlab (The Mathworks, USA) and Statistica (Statsoft, USA).

Omissions. The number and the spatial distribution of omissions were analyzed by normalizing the error percentage by the arcsin of their quadratic square (Arc-sin 2√err%; Zubin, 1935) for each quadrant (i.e., left/right and bottom/top).

Subjective epicenter. A further analysis was based on the Cartesian coordinates of the cancellation marks. Data were first cleaned by an "ad hoc" tool (VB Digital Draw readapted; VBDD) that allows exclusion of the vector coordinates of involuntary or erroneous marks (Di Luca et al., 2013). Subsequently, for each participant, we considered the (x, y) coordinates of

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[1] Timing was determined in a pilot study in which 5 participants, who had not participated in the main experiment, were presented with the two cancellation tasks. All participants completed the task within 40 seconds. Therefore, in order to increase the likelihood of omissions, time lock was fixed at 30 seconds.

any single mark. Indeed, for each cancelled target, the middle point of the mark was calculated on the *x* and *y* coordinates generated by the pressure-sensitive Ink Pen while marking down the target[2]. This methodology provided us with an extremely accurate index of the participants' attentional shifts. In particular, individual variations on the length of the marks as well as minimal directional displacements from the targets were all considered. The average middle point of all marked targets (i.e., middle points of each mark) was referred to as an individual's subjective epicenter.

First mark. This index refers to the spatial position of the (*x*, *y*) middle point coordinates of the first mark. For both the *subjective epicenter* and the *first mark* scoring, all positive/negative values refer to the right/left and top/bottom displacement with respect to the objective center (*C:* 0, 0). Points registered by VBDD readapted were converted in millimeters.

Directional Shifts. Movements within each axis (i.e., horizontal and vertical) and between marks were computed as shifts from left-to-right (or bottom-to-top), from right-to-left (or top-to-bottom) or as no-movement. The data were calculated from the first movement, subtracting each mark value from the previous one (i.e., starting from the second target cancelled out). We assigned a positive value (i.e., +1) for a left-to-right or bottom-to-top shift and a negative value (i.e., -1) for a shift in the opposite directions. All no-movements within each axis (i.e., <.3 mm) were scored as neutral (i.e., 0). The overall sum of all shifts for each participant in each matrix was entered in a targeted analysis.

Time shifts. The time spent between each mark and the next one (i.e., defined by the vector coordinates of the middle points) was recorded for each condition (i.e., left-to-right vs. right-

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[2] In order to minimize random variability in the graphic production due to executive factors (e.g., speeded performance, movement directionality), the mark weighted pressure was taken into account in computing the (*x*, *y*) coordinates of each mark:

$$\mathrm{A}\,(x;y) = \left(\frac{\sum_{i=1}^{N}(x_i \cdot p_i + x_{i+1} * p_{i+1} + \ldots + x_n * p_n)}{\sum_{i=1}^{N}(p_i + p_{i+1} + \ldots + p_n)}\ ; \ldots\right)$$

were A is a target cancelled out, x and y are the average coordinates of the mark, calculated from the average of every point (x_i, y_i) and *p* is the pressure for each point.

to-left, bottom-to-top vs. top-to-bottom) and these values were analyzed in order to assess whether reading habits influenced movement speed.

Smooth index. This index was computed on the standard deviations of 3 consecutive targets (i.e., middle points of both *x* and *y* coordinates) and indicated how participants' visuomotor scanning deviated from an optimized pathway through the targets. A high *smooth index* indicated a search pattern in which the distant targets were cancelled out instead of the proximal ones: thus, the lower the *smooth index*, the better the visuomotor exploration was.

Line bisection

The task was a computerized line bisection task (see **Figure 3.2**). To increase stimulus variability and to avoid automatic responses, two different line lengths (short, i.e., 80 mm, or long, i.e., 160 mm) were presented slightly shifted from the screen center (six different positions obtained by combining up/center/down and leftward/rightward). The mouse cursor was a vertical arrow, moving only along the horizontal axis and appearing underneath either the left or the right extreme of the line, at a fixed distance of 1 mm under the stimulus. The initial position of the mouse cursor and the position of the line on the screen were randomly assigned in each trial. Participants indicated the line midpoint by clicking the mouse with the right hand (note, left-handed participants also preferred to use the non-dominant hand). The session started with 5 practice trials, which were followed by 24 experimental trials, balanced by length. Participants sat at about 50 cm away from the screen. The bisection error was measured to the nearest millimeter, by determining the distance between the marked position and the objective center. Bisection marks to the right of the objective center were recorded as a positive value while bisection marks to the left of the center were recorded as a negative value (i.e., the objective center was assigned as 0). Line bisection task was always administered first, in order to exclude any influence of visuomotor scanning or visuospatial reorientation, possibly induced by performing cancellation tasks.

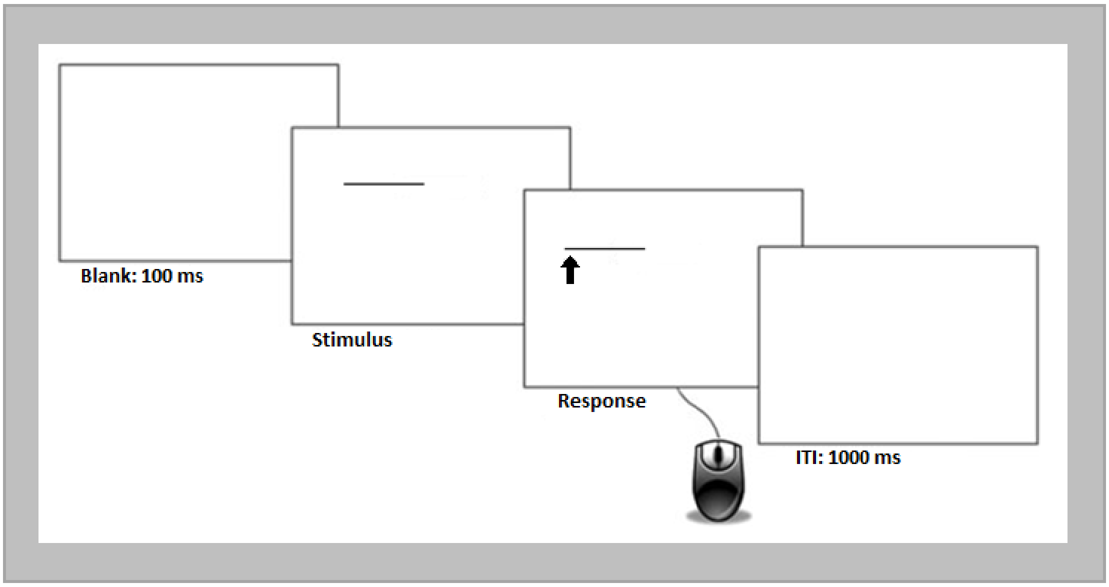

Figure 3.2. Procedure of the line bisection task. After the stimulus presentation, the participants could move the arrow cursor towards the left or towards the right, in order to bisect the line. The cursor could initially appear either at the left or at the right end and the stimulus could appear in six different positions across the screen. Two line lengths (8 and 16 cm) were used. Note, ITI = inter-trial interval.

3.3. RESULTS

Cancellation task

Omissions

Overall, participants made 272 omissions out of 7,504 possible targets[3] (3.62 % error rate; see **Table 3.1** for all means and standard deviations). Omissions analysis was calculated by normalizing the percentage of omissions by the arcsin of their square root (Zubin, 1935). On the horizontal axis we performed a 2 x 2 x 3 ANOVA (analysis of variance) with hemispace (left, right) and language (English, Hebrew) entered as within-subjects factors and reading group (MoLR, Bi, MoRL) as a between-subjects factor. The results showed no main effect of reading group, $F(2, 64)=.19$, ns, $\eta^2_p=.01$, nor of hemispace, $F(1, 64)=.01$, ns, $\eta^2_p=.01$, whereas a significant effect of language was found, $F(1, 64)=10.87$, $p<.01$, $\eta^2_p=.15$, indicating more

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[3] The time latencies employed to complete the task were analyzed by an ANOVA with language (Hebrew, English) as a within-subjects factor and reading group (MoLR, Bi, MoRL) as a between-subjects factor. No main effect or interactions were significant.

omissions with the Hebrew matrix (*M* ± *SD* for Hebrew and English matrices were respectively 2.48±2.55 and 1.58±1.92). Most importantly, the hemispace by reading group interaction was significant, *F*(2, 64)=6.74, *p*<.01, η^2_p=.17. Post-hoc comparisons[4] indicated that MoLR participants made more omissions on the right side of the matrix (*M*=1.65, *SD*=2.56) compared to the left side (*M*=.74, *SD*=1.12, *p*<.05). Additionally, the mean of rightward omissions for the MoLR group was significantly different from the mean of rightward omissions for the MoRL group (*M*=.65, *SD*=.79, *p*<.05), and marginally different from the mean of rightward omissions for the Bi group (*M*=.69, *SD*=.94, *p*=.07). Finally, the difference between the leftward (*M*=1.22, *SD*=1.44) and rightward omissions (*M*=.65, *SD*=.79) in the MoRL participants just failed to reach significance (*p*=.06), while no difference emerged in the Bi group.

There were no significant interactions between hemispace and language, *F*(1, 64)=.58, ns, η^2_p=.01, and between language and reading group, *F*(2, 64)=.96, ns, η^2_p=.03. The triple interaction was marginally significant, *F*(2, 64)=2.97, *p*=.058, η^2_p=.08. Post-hoc comparisons highlighted that MoLR participants made more rightward omissions (*M*=2.43, *SD*=3.24) than leftward omissions in the Hebrew matrix (*M*=.83, *SD*=1.19, *p*<.05), and more rightward omissions in the Hebrew matrix than rightward (*M*=.87, *SD*=1.29, *p*<.05) and leftward (*M*=.65, *SD*=1.07, *p*<.05) omissions in the English matrix.

On the vertical axis we performed a 2 x 2 x 3 ANOVA with hemispace (bottom, top) and language (English, Hebrew) as within-subjects factors and reading group (MoLR, Bi, MoRL) as a between-subjects factor, The results indicated a significant effect of language, *F*(1, 64)=11.97, *p*<.001, η^2_p=.16, which replicated the previous results on the horizontal axis (*M* ± *SD* for Hebrew and English matrices were respectively 2.48±2.55 and 1.58±1.92). There was also a significant effect of hemispace, *F*(1, 64)=7.59, *p*<.01, η^2_p=.11, with more omissions in the lower (*M*=1.22, *SD*=1.61) compared to the upper side (*M*=.79, *SD*=1.03). No other effect or interaction was significant.

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[4] Bonferroni correction was applied to all multiple comparisons.

Table 3.1. Means and standard deviations (*SD*) for *omissions* presented by hemispaces (i.e., left/right and bottom/top), for each reading group and language.

Group	**Hebrew matrix**				**English matrix**			
	Left	**Right**	**Top**	**Bottom**	**Left**	**Right**	**Top**	**Bottom**
MoLR	.8 (*1.1*)	2.4 (*3.2*)	1.5 (*1.5*)	1.7 (*2.5*)	.7 (*1.1*)	.8 (*1.3*)	.6 (*.9*)	.9 (*1.3*)
Bi	1.3 (*1.4*)	.7 (*.9*)	.8 (*.6*)	1.3 (*1.5*)	.9 (*1.2*)	.7 (*1*)	.6 (*.6*)	.9 (1. *3*)
MoRL	1.4 (*1.3*)	.7 (*.8*)	.8 (*.9*)	1.3 (*1.3*)	1.1 (*1.5*)	.6 (*.8*)	.5 (*.8*)	1.1 (*1.5*)

Subjective epicenter

Overall, the horizontal and vertical *subjective epicenter* values were respectively -0.83 mm and 1.88 mm. On the horizontal axis we first performed a *t*-test for each condition against the objective center (see **Table 3.2** for all means, standard deviations and *t*-test results). In the MoLR group we found a significant leftward bias for the *x subjective epicenter* in both the English and the Hebrew matrix, while in the Bi group no significant differences emerged in the two matrices. Finally, for the MoRL group, we found a rightward bias only in the Hebrew matrix, with no bias in the English standard version. A two-way mixed ANOVA with language (English, Hebrew) as a within-subjects factors and reading group (MoLR, Bi, MoRL) as a between-subjects factor indicated a main effect of reading group, *F*(2, 64)=9.99, *p*<.001, η^2_p=.24. Post-hoc comparisons revealed a significant difference between the MoLR group (*M*=-3.08 mm, *SD*=1.96) and both the Bi group (*M*=-.57 mm, *SD*=1.96; *p*<.05) and the MoRL group (*M*=1.36 mm, *SD*=2.43; *p*<.001), and a trend for difference between the latter two (*p*=.057). The language effect did not reach significance, *F*(1, 64)=2.93, *p*=.09, η^2_p=.04, even though the epicenter was shifted to the left in the Hebrew matrix compared to the English one (*M* ± *SD* for Hebrew and English matrices were respectively -1.25±5.34 mm and -.04±2.81 mm). Finally, the reading group by language interaction was significant, *F*(2, 64)=6.67, *p*<.01, η^2_p=.17. Post-hoc comparisons indicated that the MoLR group had a stronger leftward deviation in the Hebrew matrix (*M*=-4.66 mm, *SD*=7.36) compared to the English one (*M*=-1.39 mm, *SD*=3.47, *p*<.01).

With regard to the vertical axis, the *y subjective epicenter* significantly shifted toward the upper hemispace (see **Table 3.2**), regardless of reading group and language. A two-way mixed ANOVA showed no significant main effects or interaction.

First mark

Overall, the horizontal and the vertical *first mark* values were respectively -42.08 and 41.99. On the horizontal axis we first performed a one sample *t*-test for the average of each condition against the *x* value of the objective center. The *x first mark* averages of the English and the Hebrew matrices were both different from the objective center, showing a leftward bias in the MoLR group. In the Bi group the *x first mark* was significantly shifted toward the left in the English matrix but not in the Hebrew one. Finally, in the MoRL group a marginal rightward bias emerged in the English matrix, while no bias was found in the Hebrew one (see **Table 3.2**). A 2 x 3 mixed ANOVA on the average of the *x first mark*, with language (Hebrew, English) as a within-subjects factor and reading group (MoLR, Bi, MoRL) as a between-subjects factor showed only a significant effect of reading group, $F(2, 64)=21.32$, $p<.001$, $\eta^2_p=.4$, with all groups differing significantly from each other (MoLR group: $M=-110.6$ mm, $SD=38.27$; Bi group: $M=-38.76$ mm, $SD=93.77$; MoRL group: $M=29.34$ mm, $SD=88.53$; all $p<.01$). The main effect of language, $F(1, 64)=.53$, ns, $\eta^2_p=.01$, as well as the interaction of reading group by language, $F(2, 64)=1.34$, ns, $\eta^2_p=.04$, were both not significant.

With regard to the *y* values, the *y first mark* was constantly positioned on the upper side (i.e., with reference to the objective center) for each condition and group (**Table 3.2**). A two-way mixed ANOVA showed no significant main effects or interaction.

Table 3.2. Means (in *mm*), standard deviations (*SD*) and *t*-test results (in reference to the objective center) for *first mark* and *subjective epicenter* presented by vertical and horizontal axes, for each language and reading group.

Group	**Hebrew matrix**		**English matrix**	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**
MoLR				
First mark *df*=22	-104.2(*50.8*) *t*=-9.9, *p*<.001	42.9 (*50*) *t*=4.1, *p*<.001	-116.9 (*18.3*) *t*=-30.6, *p*<.001	49.5 (*36.9*) *t*=6.4, *p*<.001
Subjective epicenter *df*=22	-4.7 (*7.4*) *t*=-3, *p* < .01	2.4 (*2.6*) *t*=4.5, *p* <.001	-1.4 (*3.5*) *t*=-2.1, *p* < .05	2.3 (*1. 8*) *t*=6.3, *p*<.001
Bi				
First mark *df*=22	-30.4 (*87.5*) t=-1.7, ns	36 (*50.9*) t=3.4, *p*<.01	-47.1 (*100.9*) t=-2.2, *p*<.05	35.2 (*57.3*) t=2.9, *p*<.01
Subjective epicenter *df*=22	-.6 (*2.4*) t=-1.2, ns	1.7 (*1.9*) t=4.4, *p*<.001	-.6 (*1.5*) t=-1.8, ns	1.5 (*1.4*) t=4.9, *p*<.001
MoRL				
First mark *df*=20	23.1 (*90.2)* t=1.2, ns	40.2 (*49.7*) t=3.7, *p* < .01	35.6 (*88.6*) t=1.8, *p* = .08	48.4 (*42.8*) t=5.2, *p*<.001
Subjective epicenter *df*=20	1.7 (*2.2*) t=3.6, *p*<.01	1.7 (*2.08*) t=3.8, *p*<.001	*.9 (2.6)* t=1.7*,* ns	1.7 (*2.1*) t=3.7, *p*<.001

Directional shifts

Overall, the horizontal and the vertical *directional shifts* were respectively 2.74 and -4.3. A two-way mixed ANOVA with language (English, Hebrew) as a within-subjects factor and reading group (MoLR, Bi, MoRL) as a between-subjects factor showed no main effect of language, *F*(1, 64)=.71, ns, η^2_p=01. However, and most importantly, the effect of reading group was significant, *F*(2, 64)=18.35, *p*<.001, η^2_p=.36, with the MoLR group (*M*=8.72, *SD*=4.79) moving more from left-to-right than the Bi group (*M*=1.82, *SD*=8.32), and both differing from the MoRL group (*M*=-2.81, *SD*=7.72), who moved more frequently from right-to-left (*p*<.05 for all comparisons between groups). Finally, the reading group by language interaction was not significant, *F*(2, 64)=.29, ns, η^2_p=.01 (see **Figure 3.3**).

A two-way mixed ANOVA on the vertical axis showed no significant main effects or interaction.

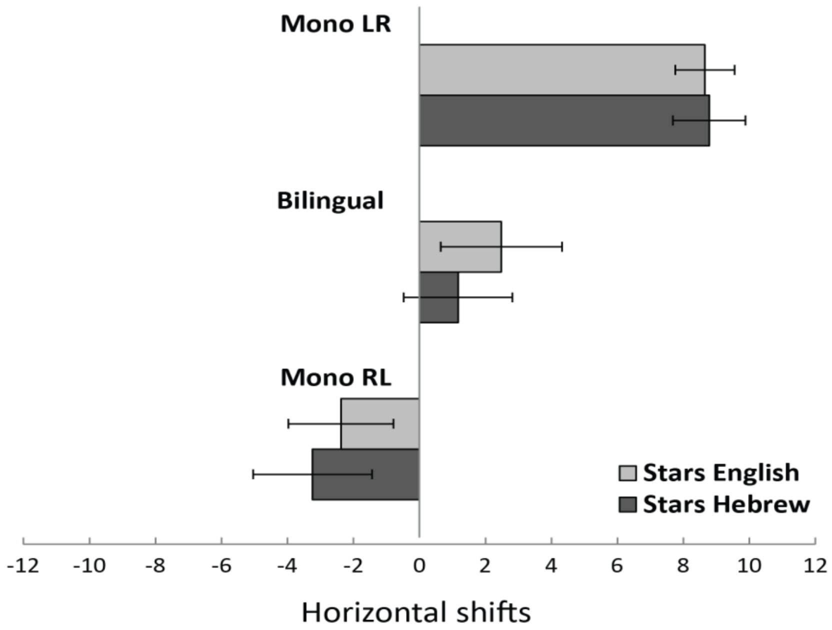

Figure 3.3. *Directional shifts*: average of the shifts, with relative errors, on the horizontal axis by language and by reading group. Positive values indicate a visual search oriented from left-to-right, whereas negative values are associated with a leftward oriented visual search.

Time shifts

Overall, the time for the horizontal and the vertical movements were 464 ms and 463 ms, respectively. A 2 x 2 x 3 ANOVA on the horizontal axis with directionality (left-to-right, right-to-left) and language (English, Hebrew) as within-subjects factors and reading group (MoLR, Bi, MoRL) as a between-subjects factor showed no main effect of reading group, $F(2, 64)=.94$, ns, $\eta^2_p=.03$, or directionality, $F(1, 64)=2.1$, ns, $\eta^2_p=.03$. However, a significant effect of language was found, $F(1, 64)=7.46$, $p<.01$, $\eta^2_p=.1$, with faster time shifts for the English matrix (*M* ± *SD* for Hebrew and English matrices were respectively 473±97 ms and 453±83 ms). No other effect or interaction was significant.

On the vertical axis the effect of language was replicated, $F(1, 64)=7.46$, $p<.01$, $\eta^2_p=.1$, with faster time shifts for the English matrix ($M \pm SD$ for Hebrew and English matrices were respectively 474±89 ms and 452±79 ms). No other effect was significant.

Smooth index

Overall, the horizontal and the vertical *smooth indexes* were respectively 14.66 mm and 14.83 mm. A 2 x 3 ANOVA on the horizontal axis with language (English, Hebrew) as a within-subjects factor and reading group (MoLR, Bi, MoRL) as a between-subjects factor showed no significant effect.

Similarly, a two-way mixed ANOVA on the vertical axis failed to show any main effect or interaction.

Line bisection

We performed a series of *t*-tests on the average of the subjective center with respect to the objective center to determine the accuracy. Results revealed that, irrespective of line length, a leftward bias emerged in the MoLR group, while a rightward bias was found in the MoRL group; no spatial bias emerged in the Bi group (see **Table 3.3** for all means, standard deviations and *t*-test results). Subsequently, the subjective displacements were entered in a 2 x 3 mixed ANOVA with line length (short, long) as a within-subjects factor and reading group (MoLR, Bi, MoRL) as a between-subjects factor. Results showed a main effect of reading group, $F(2, 64)=14.92$, $p<.001$, $\eta^2_p=.32$. Post-hoc comparisons revealed a significant difference between the MoRL group ($M=.63$ mm, $SD=.89$), the Bi group ($M=-.18$ mm, $SD=1.03$; $p<.001$) and the MoLR group ($M=-.59$ mm, $SD=.69$; $p<.001$). The difference between these two latter groups was also almost significant ($p=.055$). No other effect or interaction was significant.

Table 3.3. Means (in *mm*), standard deviations (*SD)* and *t*-test results for algebraic errors presented by line length for each reading group in the computerized line bisection.

Reading group	**Line length**	
	Short line	**Long line**
MoLR *df*=22	-.5 (*.6*) t=3.6, *p*<.01	-.7 (*.8*) t=-4.6, *p*<.001
Bi *df*=22	-.1 (*.6*) t=-.5, ns	-.3 (*1.3*) t=-1.1, ns
MoRL *df*=20	.6 (*.6*) t=3.8, *p*<.01	.7 (*1.1*) t=2.9, *p*<.01

3.4. DISCUSSION

In the present study, visuospatial performance explored by means of cancellation and bisection tasks was found to depend upon reading habits. In particular, the direction of the language system modulated on-line performance (i.e., *directional shifts*), from the beginning (i.e., *first mark*) to the end of the cancellation task (i.e., spatial location of the *omissions* and final *subjective epicenter*). In fact, monolingual readers explored and cancelled out the targets showing asymmetries predicted by their respective reading direction, while bidirectional readers did not show any significant deviation.

The analysis of *omissions* revealed the influence of reading habits on visuospatial asymmetries, regardless of the alphabetic context. Italian participants made more omissions in the right visual field, while the opposite pattern characterized the Israeli monolingual group, with bidirectional readers showing no clear spatial asymmetries. Monolingual left-to-right readers omitted more targets in the Hebrew matrix suggesting a possible perceptual cost in processing unfamiliar Hebrew graphemes. With regard to the vertical axis, all participants across reading groups explored more accurately the upper side of the visual scene, thus making more omissions in the lower space.

The influence of reading habits was confirmed by the vector analysis of the *subjective epicenter*, where a main difference between groups was found. Italians' *subjective epicenter* deviated to the left in both matrices. Monolingual Israeli participants showed a rightward bias in the Hebrew matrix only, while, in accord with the *Interactive account* hypothesis, no biases emerged in the bilingual group. These results are in line with previous studies on bilingual Israeli participants whose bidirectional scanning practices clearly modulate their visuospatial and spatial-related performances (Fagard & Dahmen, 2003; Kazandjian et al., 2009, for an egocentric reference; Nachson, 1985; Shaki, Fischer & Petrusic, 2009). This pattern of results in competing language readers, (i.e., left-right and right-left oriented) strengthens the suggestion regarding the role of scanning direction in determining visuospatial and attentional biases (Chokron et al., 1997, 2011). Interestingly, in the Italian group, the leftward epicenter was maximized in the Hebrew matrix. The perceptual cost of processing Hebrew graphemes, already suggested by the omission analysis, might have induced a left-to-right anchored visual search along with their familiar scanning habits. Finally, on the vertical axis, the *subjective epicenter* was always placed on the top part of the visual field for all reading groups.

Critically, the *first mark* analysis corroborated the group differences with Italians starting the visual search on the left hemispace, monolingual right-to-left readers starting preferentially on the right hemispace, and bidirectional readers being sensitive to the alphabetic context—they started on the left with the English matrix and did not show systematic spatial preference with the Hebrew matrix. Thus, the type of alphabetic distractors seems to have influenced the spatial location of the first mark. Importantly, in visual search tasks a preference to direct the first eye movement in the upper left quadrant has been reported (Behrmann, Watt, Black & Barton, 1997) and typically observed in cancellation tasks performed by left-to-right readers (Manly et al., 2009; Nurmi et al., 2010; Weintraub & Mesulam, 1988). However, our results show that reading habit is a strong determinant in starting the visual search and highlight that stimuli type might shape the general leftward tendency in relation to the alphabetical distracters. This interpretation is indirectly strengthened by the performance on the vertical axis, where all participants, regardless of alphabet distracters, placed the *first mark* in the visual upper hemispace.

Interestingly, the analysis of *directional shifts* revealed how the on-line visual search was oriented according to reading habits. Indeed, monolingual groups searched for targets following the direction of the reading and writing systems. Namely, the left-to-right readers made more rightward shifts and the right-to-left readers made more leftward shifts while the bilingual group showed no such lateralized pattern. Critically, during a verbal visual search task (Butler, Lawrence, Eskes & Klein, 2009) left-to-right readers performed more rightward shifts in peripersonal space, suggesting how the search pattern mimics a reading strategy. A comparable pattern has been found also in the inhibition of return effect when different reading systems were contrasted (Spalek & Hammad, 2005): while a left-to-right bias characterized the English participants, the Arabic readers showed the opposite bias. According to our results, attention seems to generate a bias that anticipates the occurrence of future information, in a direction consistent with text reading (Pollatsek, Bolozky, Well & Rayner, 1981). The influence of the reading routines on visuomotor exploration extended to the vertical axis where top-to-bottom movements were predominant.

The present study shows the extent to which the reading and writing system influences the search strategy. However, future studies are needed to investigate the online spatial distribution of attention by means of ocular search methods. Indeed, eye movement behavior in reading is known to differ across different writing systems (Deutsch & Rayner, 1999). Moreover, the distribution of eye fixations during visual search has been shown to be spatially distributed since healthy participants with left-to-right reading habits explored the left visual hemispace slightly more than the right one (Mapstone et al., 2003).

To summarize, the data from the cancellation tasks fully support the classic view according to which two different mechanisms are involved in visual scanning (Heron, 1957). The first mechanism involves scanning to the first element of a text (i.e., to the left side of space in left-to-right readers and *vice versa* in right-to-left readers), and the second one involves scanning from one word to the next in a text line (i.e., from left-to-right in English readers and *vice versa* in right-to-left readers). The multiple spatial indexes analyzed in the current study provide evidence for this model in that distinguishing between the first scanned element and the directionality of the shifts during visual search was fully dependent upon reading habits.

The line bisection performance confirmed the general findings from the cancellation task, with the spatial bias direction fully predicted by the participants' reading habits: leftward for monolingual left-to-right readers, rightward for monolingual right-to-left readers, and no bias in the bilingual group. Remarkably, the rightward bias found in monolingual right-to-left readers was strongly lateralized if compared with the bias in the cancellation task, where biomechanical variables linked to handedness (e.g., outward tensor movements preferred to inward flexor movements) might have influenced performance.

To the best of our knowledge, this is the first study in which the role of reading and writing direction in visuospatial functions (e.g., line bisection and cancellation tasks) is systematically investigated by comparing one bilingual and two monolingual groups, with opposite scanning orientation. The present study allowed us to contrast two alternative accounts of the asymmetries characterizing visuospatial performance. Due to the overall significant effect of reading habits, a *Laterality account* of visuospatial asymmetries was not supported[5]. Instead, results clearly supported an *Interactive account* according to which reading habits influence visuospatial asymmetries, despite this effect was moderated by neurobiological asymmetries orienting visuospatial attention to the left side of space. Indeed, the rightward bias of monolingual right-to-left readers did not simply mirror the leftward bias of left-to-right readers, suggesting a tuning effect of neurobiological and biomechanical tendencies.

Although attentional asymmetries have for a long time been explained mostly within the hemispheric specialization hypothesis (Bowers & Heilman, 1980; Bradshaw et al., 1987), the present study adds to the existing evidence favoring a more dynamic view according to which visuospatial attention, as probably any other cognitive function, may be only fully revealed by acknowledging cultural pressures on brain functioning.

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[5] To test any possible relation between the line bisection task and the cancellation task, we performed a series of correlation analyses between the individual spatial bias of the line bisection task and the individual *first mark/subjective epicenter* of the cancellation tasks. Importantly, and against the view of a pure *Laterality account*, no significant correlation was found.

CHAPTER 4

EDUCATION REORIENTS VISUOSPATIAL ATTENTION DURING CANCELLATION TASKS

Chapter adapted from:
Rinaldi, L., Di Luca, S., & Girelli, L. (*in preparation*). Education reorients visuospatial attention during cancellation tasks.

4.1. INTRODUCTION

Our experiences with other people and with the surrounding environment, rich in cultural determinants, inevitably shape our minds and brains. There is accumulating evidence, indeed, showing that culture can affect the neural mechanisms of low-level perceptual and attentional processes and of high-level social cognition (Han & Northoff, 2008). Among others, one of the most crucial aspects that sculpt our brain is literacy (Dehaene, Cohen, Morais & Kolinsky, 2015). Literacy implies the acquisition of knowledge related to both reading and writing at different levels, ranging from individual letters and sound units, to words and text. Learning such routines exerts a strong influence, for instance, on early visual processing (Dehaene et al., 2015) and on the orientation of visuospatial attention (Kazandjian & Chokron, 2008).

A prototypical example of the influence of culture on brain networks comes from studies investigating the effect of reading direction on visuospatial tasks. In fact, healthy individuals typically show a leftward bias, known as pseudoneglect (Bowers & Heilman, 1980), in both bisection (for a review, see Jewell & McCourt, 2000) and cancellation tasks (Vingiano, 1991). This slight, but consistent, bias has been typically interpreted as a result of hemispheric specialization (Bowers & Heilman, 1980; Kinsbourne, 1987). Nevertheless, whereas the hemispheric activation theory (Kinsbourne, 1987) might explain most of the findings in Western populations, its strength and alleged universality has been firmly challenged by various cross-cultural studies (see **Chapter 1** and **Chapter 3**).

Developmental attempts to explore the impact of schooling on visuospatial attention are also not missing. Before formal reading instruction, preschoolers' performance in bisection task is highly sensitive to the response hand: leftward biases are observed generally when bisecting with the left hand, whereas rightward biases when bisecting with the right hand (Bradshaw, Spataro, Harris, Nettleton & Bradshaw, 1988). More critically, the typical leftward bias observed in adults emerges gradually over school years (Jewell & McCourt, 2000). For instance, Chokron and De Agostini (1995) explored the influence of reading and writing exposure by comparing line bisection performance of French and Israeli preschoolers (4.5-years-old), third-grade children (8-years-old) and adults. Results showed a cultural effect since the preschool age, with Israeli children who erred more rightward than French children (Chokron & De Agostini, 1995). Yet, this pattern was maximized in the third-graders, when French children firstly showed a systematic leftward bias. These findings point to the early effect of observational routines, such as watching parents or caregivers while ordering elements in the space around us, in orienting our attention through space. This directional preference is later on strengthened by learning and practicing reading and writing (Chokron & De Agostini, 1995; see also Chokron et al., 2011; but see Fagard & Dahmen, 2003).

The present study aimed to explore the influence of schooling on visuospatial attention in a more complex task, i.e., cancellation task. Cancellation tasks are indeed typically used in the clinical assessment of unilateral spatial neglect and require the programming and execution of an online step-by-step exploration of a visual display (Vallar & Bolognini, 2012). To specifically investigate the impact of formal exposure to reading and writing both preschoolers and second-grade children were recruited as participants.

To the best of our knowledge, a single study explored developmental differences in 2-to7-yeard-old children's ability to organize serial visual search, in a paper-and-pencil version of the cancellation task (Woods et al., 2013). Results indicated that children's search direction changes most significantly between the ages of six and seven, thus approximately after two years exposure to formal reading education (Woods et al., 2013). In particular, only 7-year-old children demonstrated a clear preference for the upper left quadrant in starting the visual search. Nevertheless, the Woods et al.'s method (2013) by did not allow for a more fine analysis of the visual search during the cancellation task. For instance the number and the directionality of shifts were not recorded. On these grounds, in the present study we adopted a computerized cancellation task that allows recording of both chronometric and spatial parameters of the performance (i.e., measured in *x, y* vector coordinates). This method, proved to be sensitive to cultural differences in expert readers (see **Chapter 3**) might be ideal to capture age-related differences in children's on-line visual search.

Moreover, testing children before and after exposure to formal reading and writing practices would let us to verify the hemispheric activation theory on cancellation task. Following previous evidence (Chokron et al., 2011) we predict cultural practices to significantly impact on neurobiological mechanisms, i.e., hemispheric specialization. Specifically, we hypothesize that the starting position of the cancellation task would shift toward the left side of the space with schooling. Furthermore, we hypothesize that second-grade children would show a more optimized pathway when searching for targets than preschoolers, i.e., searching for proximal instead of distal targets. Finally, we were interested in exploring whether children' online search orientation (i.e., the number of left-to-right or right-to-left shits) is modified by the formal reading and writing practices. In particular, we hypothesize that a more rightward oriented search would emerge as a function of schooling, which would therefore play a critical role in organizing visuomotor search performance.

4.2. METHODS

Participants

Participants were 144 children aged between 5 and 8 years, drawn from the last year of kindergarten and from Grade 2 at two schools in Varese, Italy. The mean age of preschoolers (*N*=75) was 5.48 years (range: 5 years to 6 years; 38 males); for second graders (*N*=69) the mean age was 7.37 years (range: 6.5 years to 8 years; 40 males). Handedness was assessed through the performance of 10 real actions: 6 preschoolers and 19 second graders were classified as left-handers. All children had normal or corrected to normal vision, and were free of neurological disorders, learning disabilities, and history of head injury.

Apparatus

The experiment was run on a Wacom Intuos 3 graphics tablet (see **Chapter 3**).

Tasks and Stimuli

The original star cancellation task (Wilson et al., 1988) was used (**Figure 4.1**; see **Chapter 3** for further details). Furthermore, children were also presented the shapes version of the cancellation task (see **Chapter 5** for further details), although these data are not reported in the present study.

Procedure

The two cancellation tasks were administered in a counterbalanced order across participants. Each task was preceded by specific instructions indicating which target had to be searched for (i.e., the small star for the star cancellation task) and specifying to mark all the targets on the paper as rapidly and as accurately as possible, with a line stroke of the Ink Pen.

Each child was seated with the mid-sagittal plane of the trunk of his/her body transversally aligned to the center of the graphics tablet (which was placed on a desk in front of the child). Each matrix was presented individually. Children were informed of the time limit and after 60s[1] the task was interrupted. Before the experimental test, children were shown how to correctly perform the cancellation task on a practice matrix.

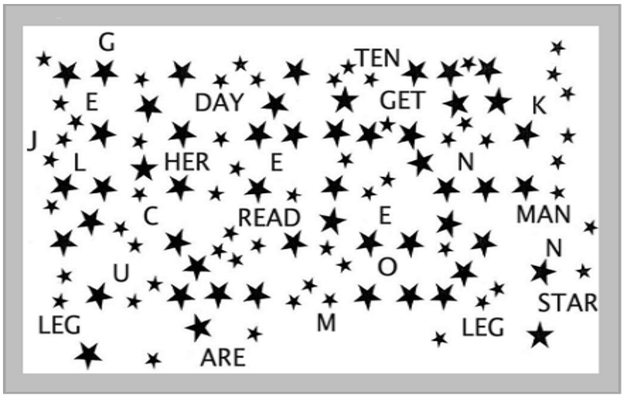

Figure 4.1. Star cancellation task (Wilson et al., 1988). The aim of the task was to cancel out all the targets (i.e., the small stars in the matrix) as rapidly and as accurately as possible. The experiment was run on a Wacom Intuos 3 graphics tablet.

Data analysis

Cancellation performance was analyzed by means of five indexes. The time for completion as well as number and location of all marked targets were recorded for each cancellation task. Coordinates of every mark (determined by the pen's pressure), and every movement (between targets) and corresponding relative response time on the *x* and *y* axes were computed: thus, data analyses are differently reported on the horizontal and on the vertical axes. Six indexes described in **Chapter** 3 were computed (*Omissions*, *Subjective epicenter*, *First mark*, *Directional shifts, Smooth*) for both the horizontal and vertical axes.

All the positive/negative values refer to the right/left and top/bottom respectively to the objective centre (*C*: 0; 0). Points registered by VBDD readapted were converted in millimeters. All data analyses were performed by Matlab (The Mathworks, USA) and Statistica (Statsoft, USA).

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[1] Timing was determined in a pilot study in which 10 children (5 preschoolers and 5 second graders), who had not participated in the main experiment, were presented with the two cancellation tasks. All children completed the task within 80 seconds. Therefore, in order to increase the likelihood of omissions, time lock was fixed at 60 seconds.

4.3. RESULTS

Omissions

Overall, children made 1903 omissions out of 8064 possible targets (24% omission rate). Omissions analysis was calculated by normalizing the percentage of omissions by the arcsin of their square root (Zubin, 1935).

On the horizontal axis, a 2x2 analysis of variance (ANOVA) with hemispace (left, right) as within-subjects factor and group (preschoolers, second graders) as between-subjects factor was performed. The results showed a main effect of group, $F(1, 141)=61.71$, $p<.001$, $\eta^2_p=.3$, with more omissions made by preschoolers ($M=9.07$, $SD=5.39$) than by second graders ($M=3.75$, $SD=4.07$). The main effect of hemispace was also significant, $F(1, 141)=11.49$, $p<.005$, $\eta^2_p=.1$, with more omissions in the right ($M=7.25$, $SD=4.19$) than in the left hemispace ($M=5.79$, $SD=3.9$). Finally, the interaction hemispace by group was not significant, $F(1, 141)=2.36$, $p=.13$.

On the vertical axis, a 2x2 ANOVA with hemispace (top, bottom) as within-subjects factor and group (preschoolers, second graders) as between-subjects factor was performed. The results showed a main effect of group, $F(1, 141)=57.17$, $p<.001$, $\eta^2_p=.29$, which replicated the previous results on the horizontal axis. The main effect of hemispace, $F(1, 141)=2.85$, $p=.1$, and the interaction, $F(1, 141)<1$, $p=.66$, were both not significant.

Subjective epicenter

Overall, the horizontal and vertical *subjective epicenter* values were -8.77 mm and 6.04 mm, respectively. We first performed a series of *t*-tests against zero (i.e., the objective centre). On the horizontal axis, there was a significant leftward bias for both preschoolers, $t(74)=-6.52$, $p<.001$ ($M=-11.69$ mm, $SD=15.54$) and second graders, $t(68)=-7.1$, $p<.001$ ($M=-5.59$ mm, $SD=4.07$) (see **Figure 4.2a**). On the vertical axis, there was a significant upward bias for both preschoolers, $t(74)=6.24$, $p<.001$ ($M=6.15$ mm, $SD=8.53$) and second graders, $t(68)=8.2$, $p<.001$ ($M=5.92$ mm, $SD=6$) (see **Figure 4.2b**).

On the horizontal axis, an independent *t*-test revealed a significant difference between groups, $t(142)=-3.02$, $p<.005$, with a reduced leftward epicenter for preschoolers than for second graders.

On the vertical axis, an independent *t*-test revealed no significant difference between groups, $t(142)<1$, $p=.85$.

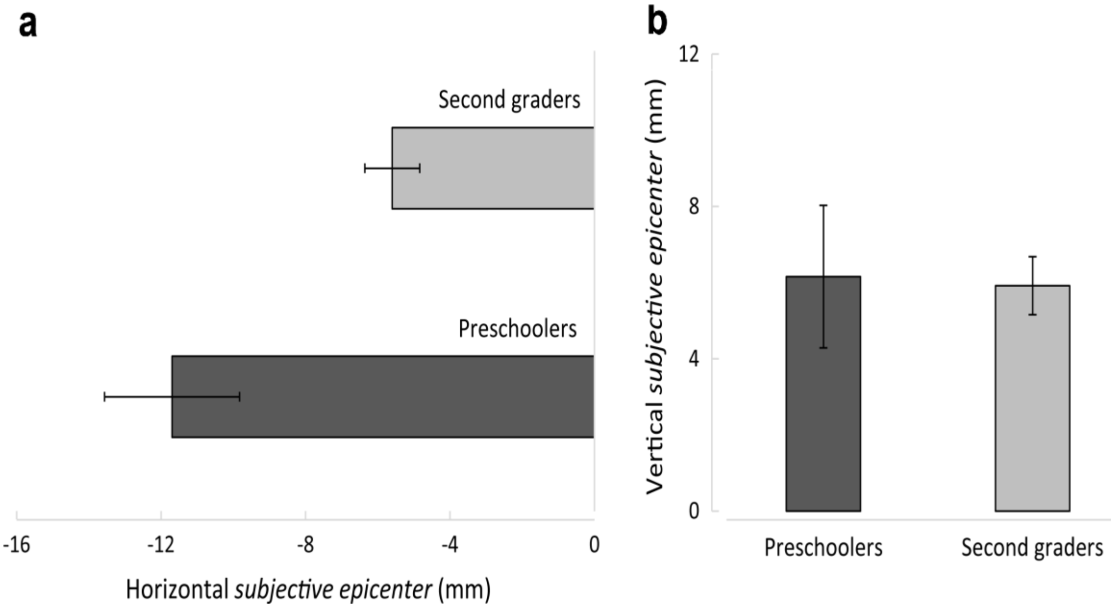

Figure 4.2. Mean *subjective epicenter* (±SEM) in the (a) horizontal and (b) vertical axes by group (preschoolers, second graders). Negative/positive score in the horizontal and vertical axes indicates a leftward/rightward and an upward/downward bias, respectively. The *subjective epicenter* was computed as the average middle point of all marked targets (i.e., middle points of each mark).

First mark

Overall, the horizontal and vertical *first mark* values were respectively 10.24 mm and 16.44 mm. We first performed a series of *t*-tests against zero (i.e., the objective centre). On the horizontal axis, the *first mark* was significantly shifted toward the right for preschoolers, *t*(74)=-3.99, *p*<.001 (*M*=32 mm, *SD*=69.57) but not for second graders, *t*(68)=-1.41, *p*=.16 (*M*=-13.43 mm, *SD*=79.09) (see **Figure 4.3a**). On the vertical axis, the *first mark* was significantly shifted upward for both preschoolers, *t*(74)=2.19, *p*<.05 (*M*=12.15 mm, *SD*=47.96) and second graders, *t*(68)=3.47, *p*<.005 (*M*=21.09 mm, *SD*=50.53) (see **Figure 4.3b**).

On the horizontal axis, an independent t-test revealed a significant difference between groups, *t*(142)=3.67, *p*<.001, with a more pronounced rightward *first mark* for preschoolers than for second graders.

On the vertical axis, an independent *t*-test revealed no significant difference between groups, *t*(142)=-1.09, *p*=.28.

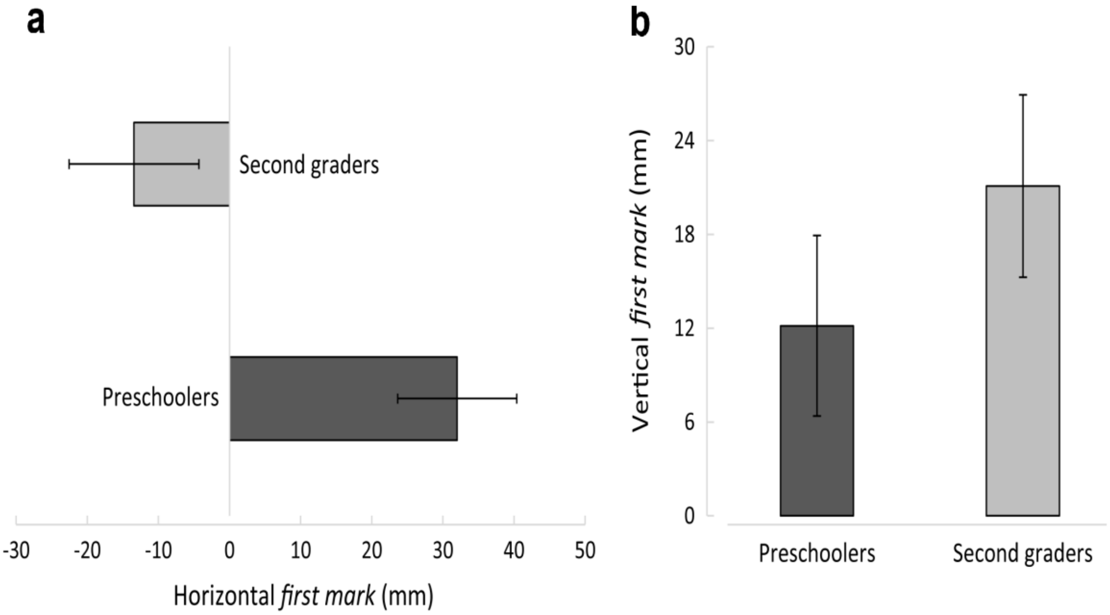

Figure 4.3. Mean *first mark* (±SEM) values in the (a) horizontal and (b) vertical axes by group (preschoolers, second graders). Negative/positive score in the horizontal and vertical axes indicates a leftward/rightward and an upward/downward bias, respectively. The *first mark* was computed as the spatial position of the (*x*, *y*) middle point coordinates of the first mark.

Directional Shifts

Overall, the horizontal and vertical *directional shifts* were respectively .34 and -1.9.

On the horizontal axis, an independent *t*-test revealed a significant difference between groups, *t*(142)=-3.66, *p*<.001, with a more rightward-oriented visual search for second graders (*M*=2.28, *SD*=6.94) than for preschoolers (*M*=-1.43, *SD*=5.08) (see **Figure 4.4a**).

On the vertical axis, an independent *t*-test revealed a significant difference between groups, *t*(142)=2.5, *p*<.05, with a more downward-oriented visual search for second graders (*M*=-3.33, *SD*=6.75) than for preschoolers (*M*=-.63, *SD*=6.22) (see **Figure 4.4b**).

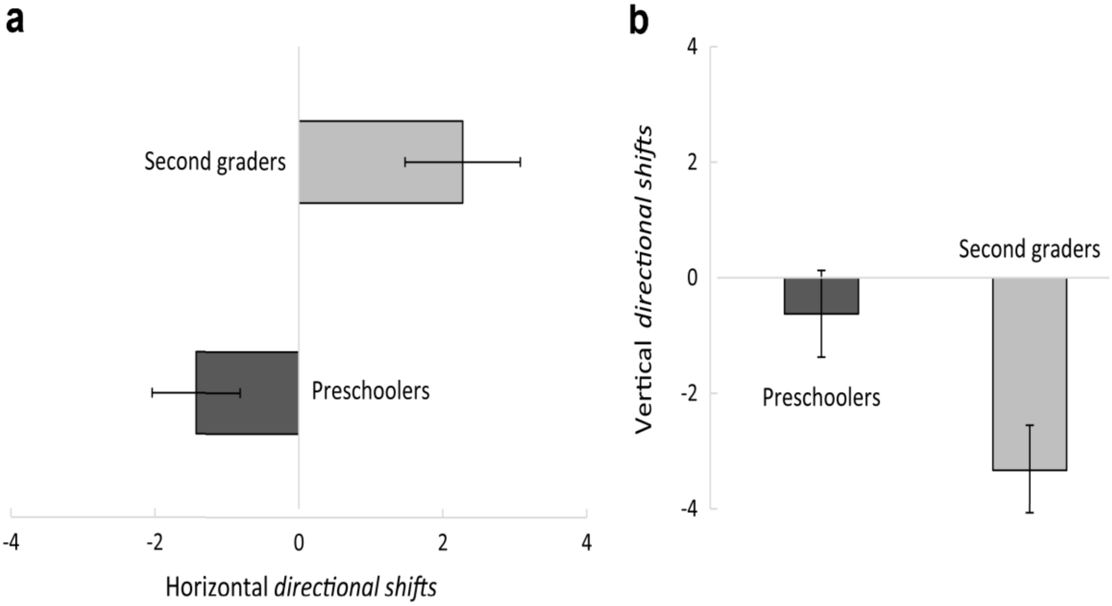

Figure 4.4. Mean *directional shifts* (±SEM) in the (a) horizontal and (b) vertical axes by group (preschoolers, second graders). In the horizontal axis, positive values indicate a visual search oriented from left-to-right, whereas negative values a search oriented from right-to-left. In the vertical axis, positive values indicate a visual search oriented from top-to-bottom, whereas negative values a search oriented from bottom-to-top.

Smooth

Overall, the horizontal and vertical *smooths* were respectively 18.8 mm and 14.39 mm.

On the horizontal axis, an independent *t*-test revealed a significant difference between groups, *t*(142)=2.1, *p*<.05, with a lower *smooth* in second graders (*M*=18 mm, *SD*=3.85) than in preschoolers (*M*=19.52 mm, *SD*=4.95).

On the vertical axis, an independent *t*-test revealed a significant difference between groups, *t*(142)=2.35, *p*<.05, with a lower *smooth* in second graders (*M*=13.89 mm, *SD*=2.54) than in preschoolers (*M*=14.85 mm, *SD*=2.32).

4.4. DISCUSSION

The present study explored the influence of schooling on visuospatial attention in a cancellation task, by comparing preschoolers and second-grade children visuomotor search behavior. Results showed that the exposure to formal education exerts a strong influence on the visual search behavior, from the starting position (i.e., *first mark*) to the online oriented path (i.e., *directional shifts*) and the overall distribution of attentional resources during cancellation task (i.e., spatial location of the *omissions* and final *subjective epicenter*). Indeed, along with an increased optimization of visuomotor scanning (i.e., *smooth*), a leftward shift of attention from preschoolers to second graders emerged in the cancellation of the first target as a preference for orienting the visual search from left-to-right. These findings, therefore, substantiate previous evidence indicating that, in Western cultures, the orientation of spatial attention shifts leftward over the course of elementary school years, as children learn to read and write in a left-right reading culture (Chokron & De Agostini, 1995; Woods et al., 2014). More generally, this evidence further supports the view that the leftward bias known as pseudoneglect (Bowers & Heilman, 1980) does not simply result from hemispheric unbalance (Bradshaw et al., 1987), but rather from a strict interplay between cultural and biological factors (Chokron et al., 2011; Rinaldi et al., 2014).

Notably, schooling had a strong impact on the *first mark* spatial position. In preschoolers, vsuospatial attention was first directed toward the right side of space across the cancellation matrix, whereas in second graders a leftward, though not significant, preference was found (see Woods et al., 2013). These results are in line with previous studies that reported a rightward bisection bias in Western preschoolers (e.g., Chokron & De Agostini, 1995). The rightward tendency has been accounted for by an unbalanced hemispheric involvement induced by unilateral limb activity, i.e., the right hand, during the task (Bradshaw et al., 1998; Sampaio, Gouarirc & Mvondo, 1995). This may also apply to the present study that, besides involving mainly right-handers children, requires major motor control than a simple manual bisection. Indeed, in the cancellation task children had to program and execute an online step-by-step visuomotor exploration, instead of a single movement as requested by line bisection. Finally, all children placed the *first mark* in the visual upper hemispace, irrespective of their level of education.

The *directional shifts* analysis allowed to investigate the scanning path followed in the visuomotor search. Results showed that schooling exerted a major impact on both the horizontal and vertical visuomotor strategy. In fact, children's search orientation changed between the five and seven years of age, thus after approximately two years of exposure to formal reading and writing education (see Woods et al., 2013). Specifically, on the horizontal axis preschoolers adopted a leftward search scanning, proceeding from right to left, as right-handedness was mainly responsible for orienting attention first to the right side of the matrix. Nevertheless, despite most of second graders were also right-handers, in this group of children there was a clear shift in the search behavior, with a prevalence of a rightward-oriented scanning. Overall, these results indicate that schooling had a strong impact on neuromuscular preferences, such headedness, in orienting attention through horizontal space. Similarly, in the vertical axis schooling reoriented the online visuomotor strategy. In particular, second graders showed a more downward-oriented search strategy than preschoolers, reflecting the typical top-to-bottom scanning of a text. Taken together, these results indicate that children from Western population start to orient their visual search from left-to-right as soon as they learn to read and write (Rinaldi et al., 2014; Goonetilleke, Lau & Shih, 2002; cf. Butler, Lawrence, Eskes & Klein, 2009).

The analysis of *omissions* showed that second graders found overall more targets than preschoolers and that all children made more *omissions* to the right than to the left hemispace. This pattern was confirmed by the more sensitive analysis of the *subjective epicenter*, where a leftward bias was found for both groups. At the same time, however, a more accentuated leftward bias was found for preschoolers than for second graders. This difference might be partially explained by the overall better performance of second graders. Nevertheless, preschoolers started the cancellation task from the right hemispace and searched for targets from right to left. Accordingly, one may have expected these children to detect more targets in the hemispace where the visual search was initiated, i.e., the right. On the other hand, we notice that preschoolers' visuomotor search was less organized than second graders' search. In fact, the higher value of *smooth* indicated that preschoolers adopted a search pattern in which the distant targets were cancelled out instead of the proximal ones. Accordingly, it is likely that preschoolers directed their attention first to the right hemispace and then they shifted attentional resources in a non-systematic fashion (i.e., not following a row by row or a column by column strategy) toward the left side of the space.

To summarize, by testing children before and after acquisition of reading and writing practices, we showed that cultural routines impact significantly on neurobiological attentional mechanisms (i.e., hemispheric specialization). These results are therefore more compatible with the view of a strict interplay between biological and cultural factors (Kazandjian & Chokron, 2008), and to a lower extent with the view of an unidirectional modulation of cerebral asymmetries on the dynamics subserving the orientation of visuospatial attention (Kinsbourne, 1987).

CHAPTER 5

SITUATING VISUOSPATIAL ATTENTION ON CULTURAL FACTORS:

Situational requirements reorient attentional resources during cancellation tasks

Chapter adapted from:
Rinaldi, L., Di Luca, S., Henik, A., & Girelli, L. (*in preparation*). Situating visuospatial attention on cultural factors: Situational requirements reorient attentional resources during cancellation tasks.

5.1. INTRODUCTION

Insofar, findings reported in **Chapter 3** and **Chapter 4** indicate that visuospatial attention is biased by reading and writing direction, with the strength of this bias dependent on an interplay between cultural expertise and biological predispositions. Nevertheless, whereas cultural practices might play a critical role in directing attention toward a certain proportion of the space in a neutral visual scene (i.e., as when performing a line bisection task), in many other situations our attention might also be driven by the context in which we act. This possibility would therefore favor the view that culture is malleable and sensitive to external cues (Oyserman, Sorensen, Reber & Chen, 2009).

There is evidence, indeed, that reading and writing habits play a relative rather than an absolute role on the spatial representation of numerical information (Fischer, Mills & Shaki, 2010; Shaki & Gevers, 2011). In fact, the directional scanning associated to reading habits can flexibly affect spatial-numerical associations (Fischer, Shaki & Cruise, 2009; Fischer et al., 2010). For instance, manipulating the position of digits within a text (i.e., placing them from left-to-right or from right-to-left) can influence the typical response-side compatibility effect between numbers and space, suggesting that the impact of reading habits is far from being persistent (Fischer et al., 2010). Similarly, the orientation of spatial-numerical associations rapidly changes depending on whether bilingual participants are processing Russian (i.e., read from left-to-right) or Hebrew (i.e., read from right-to-left) number words (Fischer et al., 2009). Thus, these studies speak in favor of a strict interplay between sensorimotor experience, such as reading and writing habits, and current constraints imposed by the task at hand, such as the effects induced by language direction manipulations, in the spatial representation of numerical information (Fischer, 2012).

Whereas an influence of situational factors has been documented in numerical cognition, quite surprisingly little is known about their influence on pure visuospatial attention. Only two studies, to the best of our knowledge, addressed the possible interplay between reading direction and situational factors. A first study by Kazandjian et al. (2010) tested different bidirectional reading groups in a bisection task of strings composed of both English and Hebrew number words, though no effect of language manipulation was found. A second study (Rinaldi et al., 2014; see **Chapter 3**) explored the role of situational factors in three groups of readers (i.e., monolingual left-to-right, bilingual, monolingual right-to-left readers) by asking participants to perform two computerized versions of the star cancellation task (Wilson et al., 1988), one with English letters and words as distractors, and one with the same distractors in Hebrew. Results indicated only a difference between reading groups, but critically no modulation of verbal distractors. Nevertheless, in the above studies, the null effect of situational factors may result from various reasons. First, in Kazandjian et al.'s (2010) study, numbers words were used and, thus, possible situational effects played by the language of the stimuli (English or Hebrew) might have been altered by numerical magnitude (see de Hevia, Girelli & Vallar, 2006). Second, in the study presented in **Chapter 3**, letters and words from different languages were used as distractors and, hence, they were mostly irrelevant to the task performance. On these grounds, in the present study we aimed at exploring whether cultural factors might be altered by situational factors, i.e., current requirements and constraints imposed by the task at hand, by means of a more systematic paradigm.

The performance of three groups with different reading habits was compared on ad-hoc versions of the cancellation task, in order to test the effect of situational requirements on the visual search. As in **Chapter 3**, we involved a first group of monolingual Italian participants, i.e., reading only from left-to-right, a second group of monolingual Israeli participants, i.e., reading only from right-to-left, and a third group of bidirectional readers, i.e., Israeli participants with Hebrew as first language and with good English proficiency. To specifically test the impact of situational factors on the online visuomotor search, three new versions of the cancellation task were designed: one composed by geometrical shapes, one by Latin letters and one by Hebrew letters. Matrices were composed by the same type of stimuli in order to emphasize the role of situational factors: for instance, in the Latin version, stimuli and distractors were both Latin letters. Whereas the geometrical version was administered to all participants, the alphabetical versions (i.e., Hebrew and Latin) were administered as a function of participants reading proficiency.

In order to rule out the confounding effect of stimuli proximity and salience during the visuomotor search, matrices were designed with a symmetrical disposition. Specifically, targets were positioned equidistant from each other, whereas distractors were placed randomly across the matrix.

We first predicted that the type of stimuli (e.g., shapes *vs.* letters) composing the visual matrix would influence the visuospatial search during the cancellation task. In particular, with the geometrical version, the three groups should adopt different spatial strategies depending on their reading habits, reflecting the influence of the culturally-oriented routines. Critically, we hypothesize that visuospatial performance should be more lateralized (i.e., in terms of starting position of the visual search and of the online visuomotor pattern) in the alphabetical matrix, compared to the geometrical one, as alphabetical stimuli should more efficiently evoke a reading scanning. This dissociation should be observed in all groups, thus indicating an influence of situational factors depending on whether participants are processing alphabetical or geometrical stimuli.

Second, we hypothesize that performance in the bilingual group should further dissociate depending on the version of the task, i.e., Hebrew or Latin version. Indeed, previous studies have shown that numerical mapping in bimanual classification tasks is prone to language manipulation (Fischer et al., 2010; Shaki & Gevers, 2011). Thus, Israeli participants with mixed reading habits (i.e., reading and writing both Hebrew and English) should not only show less consistent lateralized directional tendencies than monolingual readers, but also follow a differently oriented visuospatial search depending on the version of the task. In particular, we predict that whereas bilingual readers should search Hebrew letters in a right-to-left direction, they should search Latin letters proceeding left-to-right.

5.2. METHODS

Participants

A total of 69 participants took part in the study: 23 Italian students (7 males; *M* age=22.6±1.9, from the University of Milano-Bicocca (Italy), 23 bilingual Israeli students (6 males; *M* age=24.2±2.6 years) from the Ben-Gurion University of the Negev (Israel), and 23 Israeli ultra-Orthodox Jewish participants (16 males; *M* age=21±2.4 years). The bilingual right-to-left reading participants (Bi Group) were native-born Israelis with Hebrew as their native language, and with good English skills: they were all familiar with a left-to-right language and started to learn English from the fifth grade of primary school. Italian (MoLR Group) and Israeli ultra-Orthodox Jewish (MoRL Group) participants were all monolingual and therefore constituted a monodirectional group.

All the participants had a normal or corrected-to-normal visual acuity and were naïve with respect to the experimental hypotheses. Six participants (e.g., 1 from Bi Group, 2 from both MoLR Group and 3 from MoRL Group) were excluded a priori from the analyses due to technical problems. Laterality was assessed by using the Edinburgh Inventory (Oldfield, 1971): all participants from the MoLR Group were classified as right-handed. In the MoRL Group, 18 participants were right-handed and 5 left-handed. In the Bi Group, 20 participants were classified as right-handed and 3 as left-handed.

Apparatus

The experiment was run on a Wacom Intuos 3 graphics tablet (see **Chapter 3**).

Tasks and Stimuli

Three cancellation matrices were prepared on standard white 160 x 160 mm papers: *a*) the shapes version, *b*) the Latin version and *c*) the Hebrew version. Each matrix contained 39 targets and 204 distractors, for a total of 243 stimuli (ratio 1:5). Each target was placed at the apex of attached equilateral triangles and, thus, had the same distance from the proximal targets (26 mm) (see **Figure 5.1a**). Targets position and numerosity were identical in all the versions of the task. Specifically, each matrix had 8 targets in each of the four quadrant, 2 disposed along the vertical midline, 4 along the horizontal midline and 1 in the centre (18 in the left and 18 in the right hemispace); 49 distractors were placed in each quadrant, 4 in the vertical midline and 4 in the horizontal midline (100 in the left and 100 in the right hemispace).

In the shapes version, the target was the cross (✚) and 8 different shapes the distractors (size: 5x5 mm) (see **Figure 5.1b**). In the Latin version, the letter M was the target and 8 different letters (A, H, N, O, S, T, U, Z) the distractors. Letters were chosen for their visual symmetry and for their position in the "mental alphabet line" (11th for the target; 1st ,8th, 12th, 13th, 17th, 18th, 19th, 21th for the distractors): all the pre-oriented letters were excluded in order to not influence bias in perception (i.e., S and Z were chosen for balancing their opposite direction). Letters were presented in Times New Roman font (size: 5x5mm) (see **Figure 5.1c**). In the Hebrew version, the letter ה was the target and 8 different letters (א, ג, ל, מ, ס, צ, ש, ת) the distractors. Letters were chosen following the same criteria of the Latin version (see **Figure 5.1d**).

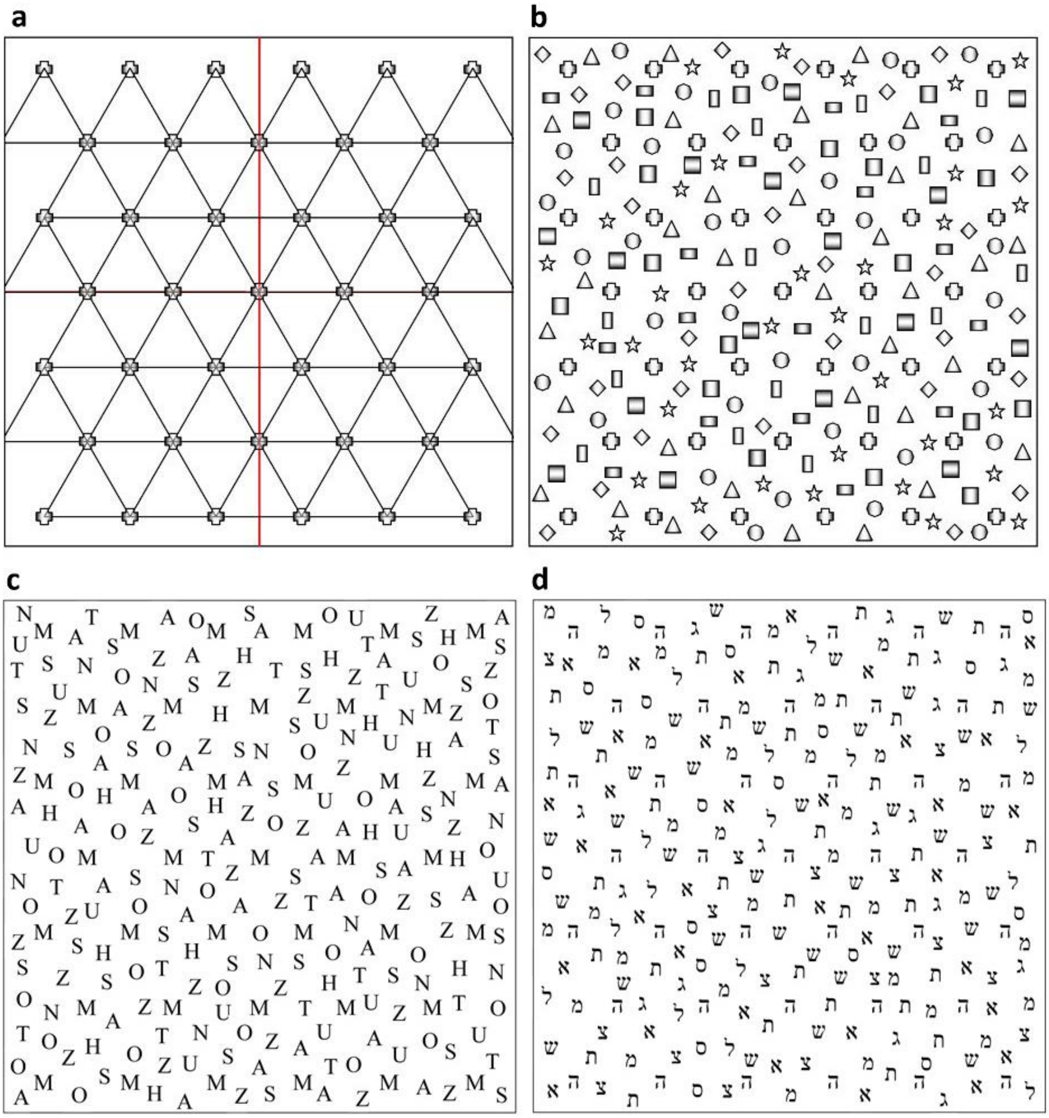

Figure 5.1. The three versions of the cancellation task. a) Targets disposition in the three versions of the cancellation task. Stimuli were disposed at the apex of invisible adjacent equilateral triangles and were equidistant from each other. The cancellation task was run on a Wacom Intuos 3 graphics tablet. b) Shapes version of the task, composed by geometrical shapes (target: cross). c) Latin version of the task, composed by Latin letters (target: letter "M"). d) Hebrew version of the task, composed by Hebrew letters (target: letter "ה").

Procedure

The three cancellation tasks were administered in a counterbalanced order across participants. Each task was preceded by instructions indicating which target had to be searched for and specifying to mark all the targets on the paper as rapidly and as accurately as possible, with a line stroke of the Ink Pen.

Each participant was seated with the mid-sagittal plane of the trunk of his/her body transversally aligned to the center of the graphics tablet (which was placed on a desk in front of the participant). Each matrix was presented individually. Participants were informed of the time limit and after 30s the task was interrupted. Before the experimental task, participants were shown how to correctly perform the cancellation on a practice matrix. The MoLR Group performed the shapes and Latin versions of the task, whereas the MoRL Group the Shapes and the Hebrew versions of the task. The Bi Group performed all the three versions of the task.

Data analysis

Cancellation performance was analyzed by five indexes. The time for completion as well as number and location of all marked targets were recorded for each cancellation. Coordinates of every mark (determined by the pen's pressure), and every movement (between targets) and corresponding relative response time on the *x* and *y* axes were computed. Cultural and situational effects are expected on the horizontal axis, with the vertical axis serving mainly as the control condition. Hence, only data on the horizontal axis will be considered in the reported analysis.

Five of the six indexes described in **Chapter 3** were computed (*Omissions*, *Subjective epicenter*, *First mark*, *Directional shifts, Smooth*).

All the positive/negative values refer to the right/left respectively to the objective centre (*C*: 0; 0). Points registered by VBDD readapted were converted in millimeters. All data analyses were performed by Matlab (The Mathworks, USA) and Statistica (Statsoft, USA).

5.3. RESULTS

Since the two monolingual groups performed only two versions of the task (MoLR Group: shapes and Latin versions; MoRL Group: shapes and Hebrew versions) different analyses were computed for each dependent variable. In particular, a first analysis compared the performance of the three groups in the shapes version of the task. A second analysis, limited to the Bi Group, explored performance differences in the three versions of the task. A third analysis compared the MoLR Group and the Bi Group in the shapes and in the Latin versions of the task. A fourth analysis compared the MoRL Group and the Bi Group in the shapes and in the Hebrew versions of the task. Finally, a fifth analysis compared the performance of the MoLR Group and of the MoRL Group in the alphabetical version of the task (i.e., Latin for the MoLR Group, Hebrew for the MoRL Group).

Omissions

Overall participants made 370 omissions out of 6279 possible targets (5.9% omission rate; see **Table 5.1** for all means and standard deviations). Omissions analysis was calculated by normalizing the percentage of omissions by the arcsin of their square root (Zubin, 1935).

A 2x3 repeated measures analysis of variance (ANOVA) in the shapes version of the task, with hemispace (left, right) as within-subjects factor and reading group (MoLR, Bi, MoRL) as between-subjects factor, showed a significant interaction hemispace by reading group, $F(2, 66)=9.1$, $p<.001$, $\eta^2_p=.22$. Post-hoc comparisons[1] indicated that the MoLR Group made more omissions in the right than in the left hemispace ($p<.01$).

A 2x3 ANOVA with hemispace (left, right) and version of the task (shapes, Latin, Hebrew) as within-subjects factors, performed only on the Bi Group, showed a significant interaction hemispace by version of the task, $F(2, 44)=3.19$, $p<.05$, $\eta^2_p=.13$. Post-hoc comparisons indicated that the Bi Group made more more omissions in the left hemispace of the shapes version than in all other conditions (all *p*s<.05), except for the right hemispace in the shapes and in the Latin versions of the task. Moreover, the Bi Group made fewer omissions in the right hemispace of the Hebrew than of the Latin version of the task ($p < .05$).

A 2x2x2 ANOVA with version of the task (shapes, Latin) and hemispace (left, right) as within-subjects factors and with reading group (MoLR, Bi) as between-subjects factor, showed a significant effect of the version of the task, $F(1, 44)=6.99$, $p<.05$, $\eta^2_p=.14$, with more omissions in the shapes compared to the Latin version. Moreover, a significant effect of hemispace was found, $F(1, 44)=12.13$, $p<.01$, $\eta^2_p=.22$, with more omissions in the right than in the left hemispace. Finally, a significant interaction hemispace by reading group was found, $F(1, 44)=8.23$, $p<.01$, $\eta^2_p=16$. Post-hoc comparisons indicated that the MoLR Group made more omissions in the right than in the left hemispace ($p < .05$).

A 2x2x2 ANOVA with version of the task (shapes, Hebrew) and hemispace (left, right) as within-subjects factors and with reading group (Bi, MoRL) as between-subjects factor,

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[1] Scheffè correction was applied in this study to test all the unplanned comparisons with a conservative approach.

showed a significant effect of the version of the task, *F*(1, 44)=5.95, *p*<.05, η^2_p=.12, with more omissions in the shapes than in the Hebrew version. Moreover, a significant effect of hemispace was found, *F*(1, 44)=7.52, *p*<.01, η^2_p=.15, with more omissions in the left than in the right hemispace. Finally, a significant effect of reading group was found, *F*(1, 44)=4.49, *p*<.05, η^2_p=.1, with more omissions in the MoRL Group than in the Bi Group.

In order to compare the performance of monolingual readers on alphabetical matrices, a 2x2 ANOVA with hemispace (left, right) as within-subjects factor and reading group (MoLR, MoRL) as between-subjects factor was performed. Results showed a main effect of reading group, *F*(1, 44)=6.21, *p*<.05, η^2_p=.12, with more omissions in the MoRL Group than in the MoLR Group. Moreover, a significant interaction hemispace by reading group was found, *F*(1, 44)=12.29, *p*<.005, η^2_p=.22. Post-hoc comparisons indicated less omissions in the left hemispace for the MoLR Group than in all other conditions (all *ps*<.05).

Table 5.1. Means and standard deviations (*SD*) for *omissions* presented by hemispace (i.e., left and right), reading group and version of the task.

Group	**Shapes**		**Latin**		**Hebrew**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
MoLR	.9 (*1.1*)	1.7 (*1.5*)	.3 (*.9*)	.9 (*1.3*)		
Bi	1.7 (*2.4*)	1.2 (*1.5)*	.8 (*1.4*)	1 (*1.2*)	.83 (*2.1*)	.5 (*1.7*)
MoRL	1.9 (*1.3*)	1.4 (*1.1*)			1.4 (*1.2*)	1 (*1.2*)

Subjective epicenter

The overall horizontal *subjective epicenter* was -.69 mm. We first performed a series of *t*-tests against zero (i.e., the objective centre). There was a significant leftward bias for the MoLR Group in the shapes and in the Latin versions of the task, whereas no bias was found in the Bi Group and in the MoRL Group (see **Table 5.2** for all means, standard deviations and *t*-test results; see also **Figure 5.2**).

An univariate ANOVA on the shapes version of the task with reading group (MoLR, Bi, MoRL) as between-subjects factor showed a significant difference between groups, *F*(2, 66)=3.17, *p*<.05, η^2_p=.09, with a more leftward *subjective epicenter* in the MoLR Group than in the MoRL Group (*p*<.02).

A further univariate ANOVA, performed only on the Bi Group, with version of the task (shapes, Latin, Hebrew) as within-subjects factor, did not reveal any significant effect.

A 2x2 ANOVA with version of the task (shapes, Latin) as within-subjects factor and with reading group (MoLR, Bi) as between-subjects factor revealed a marginally significant effect of the version of the task, $F(1, 44)=3.56$, $p=.06$, $\eta^2_p=.08$, with a *subjective epicenter* shifted toward the left in the shapes compared to the Latin version. Moreover, a significant effect of reading group was found, $F(1, 44)=4.89$, $p<.05$, $\eta^2_p=.1$, with a more leftward *subjective epicenter* in the MoLR Group than in the Bi Group.

A 2x2 ANOVA with version of the task (shapes, Hebrew) as within-subjects factor and reading group (Bi, MoRL) as between-subjects factor, did not reveal any significant effect.

In order to compare the performance of monolingual readers on alphabetical matrices, we performed a paired sample *t*-test between the MoLR Group and the and MoRL Group, which showed a more leftward *subjective epicenter* in the MoLR Group than in the MoRL Group, $t(22)=-2.5$, $p<.05$,.

Table 5.2. *T*-tests results (in reference to the objective center) for *first mark* and *subjective epicenter* presented by version of the task and by reading group.

Groups	Shapes	Latin	Hebrew
MoLR			
First mark	$t=-6.3$, $p<.001$	$t=-21.9$, $p<.001$	
Subjective epicenter	$t=-3.4$, $p<.01$	$t=-3.5$, $p<.01$	
Bi			
First mark	$t=-2.5$, $p<.05$	$t=-4.3$, $p<.01$	$t=-.1$, ns
Subjective epicenter	$t=-1.7$, ns	$t=-.9$, ns	$t=.3$, ns
MoRL			
First mark	$t=.3$, ns		$t=2.2$, $p<.05$
Subjective epicenter	$t=-.02$, ns		$t=.8$, ns

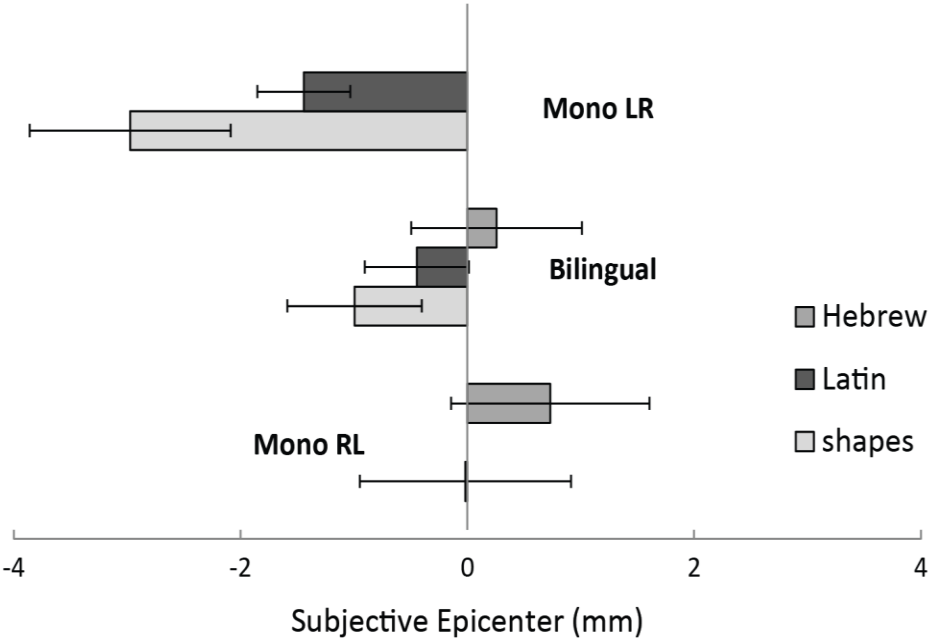

Figure 5.2. Mean *subjective epicenter* (±SEM), by version of the task (Hebrew, Latin, shapes) and by reading group (MoLR Group, Bi Group, MoRL Group). Negative/positive score indicates leftward/rightward bias. The *subjective epicenter* was computed as the average middle point of all marked targets (i.e., middle points of each mark).

First mark

Overall, the horizontal *first mark* was -20.21 mm. We first performed a series of *t*-tests against zero (i.e., the objective centre). The *first mark* was significantly shifted toward the left by both the MoLR Group and the Bi Group in the shapes and in the Latin versions of the task, whereas no bias was found for the latter group in the Hebrew version of the task. Finally, in the MoRL Group no bias was found in the shapes version, whereas a rightward starting preference was observed in the Hebrew version of the task (see **Table 5.2** for all means, standard deviations and *t* test results; see also **Figure 5.3**).

An univariate ANOVA on the shapes version of the task with reading group (MoLR, Bi, MoRL) as between-subjects factor showed a significant difference between groups, $F(2, 66)=5.41$, $p<.01$, $\eta^2_p=.14$, with a more leftward *first mark* for the MoLR Group than the MoRL Group ($p<.01$), and a trend between the Bi Group and the MoRL Group, with a more rightward shift of the *first mark* for the latter group ($p=.057$).

A further univariate ANOVA, performed only on the Bi Group, with version of the task (shapes, Latin, Hebrew) as within-subjects factor revealed a main effect of the version of the task, $F(2, 44)=4.61$, $p<.05$, $\eta^2_p=.17$, with the *first mark* positioned significantly more leftward in the Latin than in the Hebrew version of the task ($p<.05$).

A 2x2 ANOVA with version of the task (shapes, Latin) as within-subjects factor and with reading group (MoLR, Bi) as between-subjects factor revealed a main effect of the version of the task, $F(1, 44)=8.54$, $p<.01$, $\eta^2_p=.16$, with a *first mark* positioned significantly more leftward in the Latin than in the shapes version. Moreover, the effect of reading group, $F(1, 44)=5.68$, $p < .05$, $\eta^2_p=.11$, revealed a more pronounced leftward bias in the MoLR Group than in the Bi Group.

A 2x2 ANOVA with version of the task (shapes, Hebrew) as within-subjects factor and reading group (Bi, MoRL) as between-subjects factor revealed a main effect of the version of the task, $F(1, 44)=4.74$, $p<.05$, $\eta^2_p=.1$, with a more rightward bias in the Hebrew than in the shapes version. Additionally, the main effect of reading group, $F(1, 44)=5.04$, $p<.05$, $\eta^2_p=.1$, revealed a more rightward bias in the MoRL Group than in the Bi Group.

In order to compare the performance of monolingual groups on alphabetical matrices, we performed a paired sample *t*-test between the MoLR Group and the MoRL Group, which showed that the *first mark* was positioned significantly more leftward in the MoLR Group than in the MoRL Group, $t(22)=-7.34$, $p<.001$.

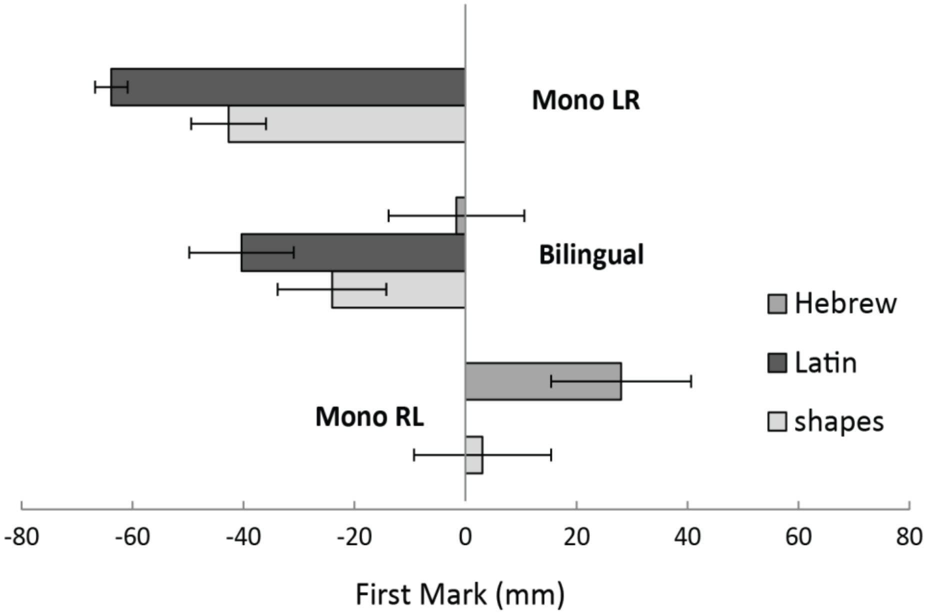

Figure 5.3. Mean *first mark* (±SEM), by version of the task (Hebrew, Latin, shapes) and by reading group (MoLR Group, Bi Group, MoRL Group). Negative/positive score indicates leftward/rightward bias. The *first mark* was computed as the spatial position of the (*x*, *y*) middle point coordinates of the first mark.

Directional Shifts

Overall, the horizontal *directional shifts* index was 2.17 (see **Figure 5.4**). An univariate ANOVA on the shapes version of the task with reading group (MoLR, Bi, MoRL) as between-subjects factor showed a significant difference between groups, $F(2, 66)=5.38$, $p<.01$ $\eta^2_p=.17$, with more left-to-right shifts for the MoLR Group ($p<.01$) and the Bi Group ($p<.01$) than for the MoRL Group.

A further univariate ANOVA only on the Bi Group with version of the task (shapes, Latin, Hebrew) as within-subjects factor revealed a main effect of the version of the task, $F(2, 44)=4.38$, $p < .05$, $\eta^2_p=.17$, with more left-to-right shifts for the Latin ($p<.01$) and the shapes version of the task ($p<.01$) than for the Hebrew one.

A 2x2 ANOVA with version of the task (shapes, Latin) as within-subjects factor and with reading group (MoLR, Bi) as between-subjects factor revealed a significant effect of the version of the task, $F(1, 44)=7.38$, $p<.01$, $\eta^2_p=.14$, with more left-to-right shifts in the Latin than in the shapes version. The main effect of reading group, $F(1, 44)=9.08$, $p<.01$, $\eta^2_p=.17$, revealed that the MoLR Group made more rightward shifts than the Bi Group. Finally, the interaction version of the task by reading group was significant, *F*(1, 44)=5.05, $p<.05$, $\eta^2_p=.1$. Post-hoc comparisons indicated more left-to-right shifts in the MoLR Group with the Latin version than in all the other conditions (all *ps*<.05).

A 2x2 ANOVA with version of the task (shapes, Hebrew) as within-subjects factor and reading group (Bi, MoRL) as between-subjects factor revealed a main effect of the version of the task, *F*(1, 44)=8.19, $p < .01$, $\eta^2_p=.16$, with more left-to-right shifts in the Hebrew than in the shapes version. Additionally, the main effect of reading group was marginally significant, *F*(1, 44)=3.25, $p=.06$, $\eta^2_p=.07$, revealing more rightward shits for the MoRL Group than for the Bi Group.

In order to compare the performance of monolingual groups on alphabetical matrices, we performed a paired sample *t*-test between the MoLR Group and the MoRL Group, which showed that MoLR Group made more rightward shifts than MoRL Group, *t*(22)=4.83, $p<.001$.

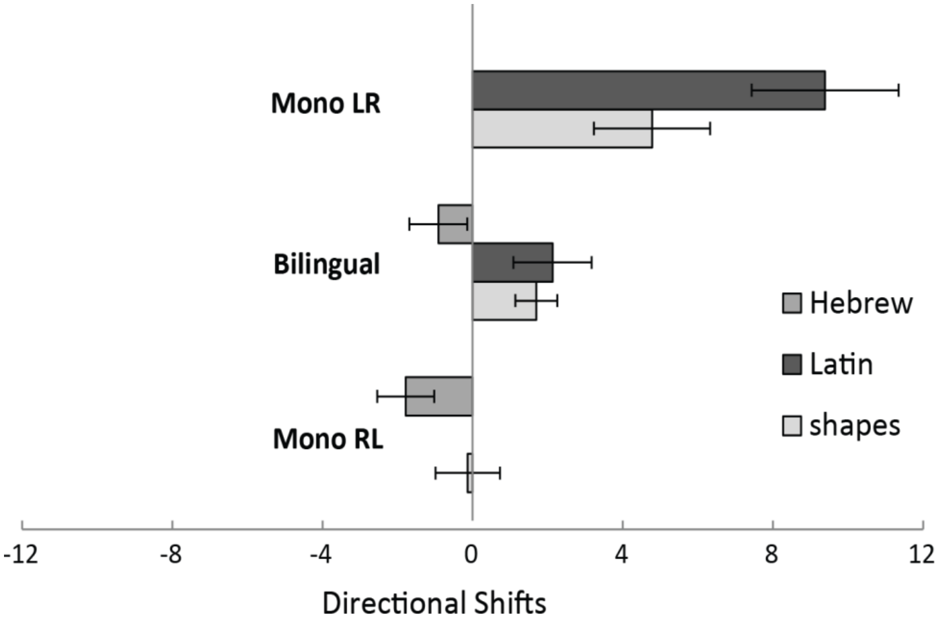

Figure 5.4. Mean *directional shifts* (±SEM), by version of the task (Hebrew, Latin, shapes) and by reading group (MoLR Group, Bi Group, MoRL Group). Positive values indicate a visual search oriented from left-to-right, whereas negative values are associated with a leftward oriented visual search.

Shifts Time

Overall, the horizontal *shifts time* was 728 ms (see **Figure 5.5**). A 2x3 repeated measures analysis of variance (ANOVA) on the shapes version of the task, with direction of the shifts (left-to-right, right-to-left) as within-subjects factor and reading group (MoLR, Bi, MoRL) as between-subjects factor, did not reveal any significant effect.

A 2x3 ANOVA with direction of the shifts (left-to-right, right-to-left) and version of the task (shapes, Latin, Hebrew) as within-subjects factors, performed only on the Bi Group, revealed a main effect of the version of the task, $F(2, 44)=7.44$, $p<.01$, $\eta^2_p=.25$, with faster shifts time in the Latin than in the Shapes ($p<.005$) and Hebrew ($p<.01$) versions of the task.

A 2x2x2 ANOVA with version of the task (shapes, Latin) and direction of the shifts (left-to-right, right-to-left) as within-subjects factors and with reading group (MoLR, Bi) as between-subjects factor, revealed a main effect of the version of the task, $F(1, 44)=24.85$, $p<.001$, $\eta^2_p=.36$, with slower *shifts time* for the shapes than for the Latin version. A significant interaction direction of the shifts by reading group was found, $F(1, 44)=3.96$, $p<.05$, $\eta^2_p=.08$. Post-hoc comparisons indicated that right-to-left shifts of the MoLR Group were significantly slower than all the other conditions (all *ps*<.05). Finally, the triple interaction was significant, $F(1, 44)=6.17$, $p<.05$, $\eta^2_p=.12$. Post-hoc comparisons indicated that the left-to-right shifts of the MoLR Group in the Latin version were significantly faster than all the others conditions (all *ps*<.05).

A 2x2x2 ANOVA with version of the task (shapes, Hebrew) and direction of the shifts (left-to-right, right-to-left) as within-subjects factors and with Reading group (Bi, MoRL) as between-subjects factor, revealed a main effect of reading group, $F(1, 44)=10.16$, $p<.01$, $\eta^2_p=.19$, with shifts of the MoRL Group significantly slower than those of the Bi Group.

In order to compare the performance of monolingual readers on alphabetical matrices, a 2x2 ANOVA with direction of the shifts (left-to-right, right-to-left) as within-subjects factor and reading group (MoLR, MoRL) as between-subjects factor was performed. Results showed a main effect of reading group, $F(1, 44)=9.73$, $p<.01$, $\eta^2_p=.18$, with slower *shifts time* for the MoRL Group than for the MoLR Group. Moreover, a significant interaction direction of the shifts by reading group was found, $F(1, 44)=9.29$, $p<.01$, $\eta^2_p=.17$. Post-hoc comparisons indicated faster left-to-right shifts for the MoLR Group than for all the other conditions (all *ps*<.05).

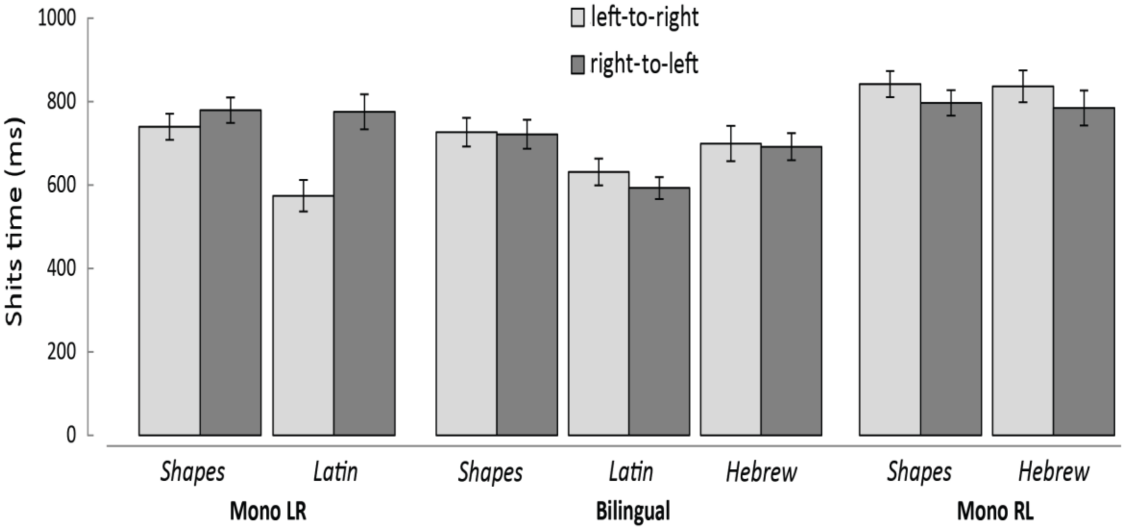

Figure 5.5. Mean *shits time* (±SEM), by version of the task (Hebrew, Latin, shapes) and by reading group (MoLR Group, Bi Group, MoRL Group). The *shits time* was computed as the time spent between each mark and the next one (i.e., defined by the vector coordinates of the middle points) as a function of movement direction (i.e., left-to-right or right-to-left).

5.4. DISCUSSION

The present study explored the possible interplay between cultural factors, i.e., reading habits, and situational factors, i.e., current requirements and constraints imposed by the task at hand, on the allocation of visuospatial attention resources during cancellation tasks. Overall, results from three different reading groups (e.g., monolingual left-to-right, monolingual right-to-left and bilingual readers) in three versions of the cancellation task (one composed by geometrical shapes, one by Latin and one by Hebrew letters) showed that participants adapted their habitual visual search depending on situational requirements.

According to previous evidence (see **Chapter 3**) the direction of the language system modulated the on-line performance (i.e., directional shifts), from the beginning (i.e., *first mark*) to the end of the cancellation task (i.e., spatial location of the omissions *and final subjective epicenter*). In particular, the visual search was mainly oriented from left-to-right and from right-to-left in Italian and Israeli monolingual readers, respectively, whereas it was less lateralized in bilingual readers, regardless of the stimuli that had to be processed. Nevertheless, the influence of reading habits on visuospatial performance was further modulated by situational requirements. First, monolingual participants followed a more lateralized search (i.e., in terms of starting position of the visual search and of the online visuomotor pattern) in the alphabetical version, compared to the geometrical one. It is therefore likely that alphabetical stimuli induced a visual search that resembled the scanning adopted during the reading or writing of a written text. Second, and critically, the visuospatial performance in the bilingual group dissociated depending on whether participants searched for targets in the Hebrew or in the Latin version of the task. Indeed, whereas bilingual participants searched for Hebrew letters in a right-to-left direction, they searched for Latin letters in a left-to-right direction. These findings clearly demonstrate that spatial and chronometric parameters of cancellation tasks adapt flexibly as a function of a strict interplay between habitual scanning habits and situational requirements.

The analyses of *omissions* showed that all participants found more targets in the alphabetical than in the shapes version of the task, a pattern that might be accounted for by a possible perceptual cost in processing less familiar stimuli. Importantly, the spatial distribution of *omissions* revealed the influence of reading direction, with more omissions in the right hemispace for the MoLR Group and *vice versa* for the MoRL Group. Furthermore, according to our hypothesis, the Bi Group performance was affected by language manipulation, with more omissions in the left hemispace in the Hebrew version of the task and more omissions in the right hemispace in the Latin version of the task. Interestingly, a greater inattention for the right hemispace of a geometrical cancellation matrix than of a verbal matrix was previously reported (Vingiano, 1991). The non-lateralized pattern with verbal material was accounted for by the right hemisphere activation induced by visuospatial task and by the concomitant activation of the left hemisphere induced by alphabetical stimuli (Kinsbourne, 1987; Vingiano, 1991). The present study, therefore, suggests more caution in interpreting visuospatial asymmetries only in terms of hemispheric involvement and speaks in favor of a critical role of cultural factors (Geldmacher & Alahj, 1999; see **Chapter 2** and **Chapter 3**).

The influence of reading habits and language manipulation was confirmed by the more sensitive analyses of the *subjective epicenter.* Overall, a leftward bias characterized the MoLR Group performance in all the versions of the tasks, while no lateralized bias was found for the other groups. A significant difference between monolingual groups was found, indicating that visuospatial attention was differently allocated as a function of reading direction (**Chapter 3**). Moreover, both the MoLR Group and the Bi Group showed a more leftward *subjective epicenter* in the shapes than in the Latin version of the task. Nevertheless, no influence of situational requirements emerged in the Bi Group, although the pattern reflected the omissions spatial distribution. It is therefore likely that participants made more omissions toward the horizontal midpoint of the cancellation task and, consequently, a statistical difference emerged only in the *omissions* analyses, where a discrete operationalization of space was applied (i.e., left vs. right hemispace).

Critically, *first mark* analyses supported the strict interplay between cultural and situational factors. Indeed, we replicated the critical impact of overlearned scanning routines on the starting position of the visual search (see **Chapter 3**). For instance, the MoLR Group positioned the *first mark* in the shapes version of the task in the left hemispace, whereas no bias was found in the MoRL Group. Importantly, monolingual readers positioned the *first mark* in the Latin and in the Hebrew versions in the left and in the right hemispace, respectively. This difference between the geometrical and the alphabetical versions of the task indicates an effect of situational requirements on the visuospatial performance. More critically, a dissociation was found in the Bi Group, with a leftward preference for the Latin version of the task and a rightward preference for the Hebrew version of the task. Hence, these findings demonstrate that the starting position of a cancellation task is modulated not only by overlearned scanning habits, but also by current constraints imposed by the task at hand.

The *directional shifts* analyses allowed us to explore the directionality of the movements during the cancellation task. Results showed that monolingual groups searched for targets following the direction of their reading and writing systems. Left-to-right readers made more rightward shifts, right-to-left readers made more leftward shifts, while bilingual readers showed no lateralized pattern. Critically, the impact of situational factors was reflected also on the on-line visual search pattern. Indeed, monolingual participants performed more lateralized movements in the alphabetical than in the shapes version of the task. Moreover, bilingual participants adapted their strategy depending on the language of the task at hand. Specifically, they searched for Hebrew letters following a more leftward oriented pattern than when searching for Latin letters. These results indicate, therefore, that healthy individuals do not universally orient their visual search from left-to-right (Butler et al., 2009; Mapstone et al., 2003), but rather as a function of both reading habits and situational requirements.

Finally, analyses on *Shifts Time* showed that the MoLR Group performed faster shifts from left-to-right than from right-to-left in the Latin version of the task. Interestingly, movements of the MoRL Group were overall slower than those of the other groups. To account for this finding, we notice that right-handers show a natural biomechanical preference in performing outward tensor movements than inward flexor movements (Brown, Knauft & Rosenbaum, 1948; Dreman, 1974; see **Chapter 3**). Hence, the experience with a leftward oriented language might not have completely reversed the natural tendency in making left-to-right hand movements.

To summarize, previous evidence demonstrated that neurobiological asymmetries orienting visuospatial attention to the left side of space are modulated by directional routines related to reading and writing practices (Rinaldi et al., 2014; Chokron & Imbert, 1993). Nevertheless, task demands have been shown to strictly interplay with reading habits in the spatial representation of numerical and non-numerical sequences (Fischer et al., 2009, 2010; Shaki & Gevers, 2011). Here the influence of situational factors was extended for the first time to the allocation of attentional resources during a cancellation task. Therefore, the present findings suggest that situational factors interplay with cultural, i.e., reading habits, and biological factors, i.e., right hemispheric specialization, in orienting visuospatial attention.

SMELLING THE SPACE AROUND US:

Odor pleasantness rapidly shifts visuospatial attention in humans

Chapter adapted from:
Rinaldi, L., Maggioni, E., Olivero, N., Maravita, A., & Girelli, L. (*under review*). Smelling the space around us: Odor pleasantness rapidly shifts visuospatial attention in humans.

6.1. INTRODUCTION

> *'Don Abbondio and Perpetua needed no keys to enter their house. With every step they took along the passage, they became more conscious of an odour, a poisonous smell, a pestilential stink, which almost seemed to push them back again.'*
>
> – Manzoni (1827/1983, p. 561)

Odor pleasantness has an important influence on human cognition, behavior and emotions (Holland, Hendriks & Aarts, 2005). Discriminating between pleasant and unpleasant odors is crucial for regulating adaptive and reproductive behaviors in humans and in many other species (Auffarth, 2013; Haddad et al., 2010). Pleasant and unpleasant odors are usually evaluated at different speed (Bensafi, Rouby, Farget, Vigouroux & Holley, 2002b). Avoidance of unpleasant odors tends to be rapid, as they are often associated to potential danger, whereas pleasant odors usually induce prolonged approaching behaviors (Boesveldt, Frasnelli, Gordon & Lundström, 2010; Knasko, 1995). Similar facilitation in reacting to negative, fear-relevant stimuli extends to other sensory modalities, such as vision (e.g., Öhman, Flykt & Esteves, 2001), disclosing the human ability to rapidly detect information that is critical for survival, and promptly adjust behavior (Mineka & Öhman, 2002).

The processing of pleasant and unpleasant odors is known to modulate psychophysiological markers of arousal (Croy, Maboshe & Hummel, 2013; Miltner, Matjak, Braun, Diekmann & Brody, 1994), with unpleasant odors significantly increasing heart rate (Bensafi et al., 2002a). Furthermore, brain circuits known to be involved in approach and avoidance behaviors, also underpin the discrimination between pleasant and unpleasant odors (Bensafi, Sobel & Khan, 2007; Zelano, Montag, Johnson, Khan & Sobel, 2007). More specifically, discrimination of odor pleasantness is associated with activations of the postero-medial and lateral portions of the orbitofrontal cortex (Grabenhorst, Rolls, Margot, da Silva & Velazco, 2007; Rolls, Kringelbach & De Araujo, 2003), an area critical for integrating sensory perception with hedonic experience and emotional processing (Kringelbach, 2005).

However, while previous work on odor valence has mainly focused on the speed of reaction to odors, the pattern of spatial orienting that follows such reactions still needs to be clarified, due to its critical importance for any approach and avoidance behaviors. In fact, humans typically respond to stimuli according to their valence, by moving towards positive stimuli and moving away from negative ones (Seibt, Neumann, Nussinson & Strack, 2008; Strack & Deutsch, 2004). It is therefore reasonable that they might take advantage of similar spatial strategies when they encounter an odor. Nevertheless, whether odor pleasantness automatically modulates spatial orienting in humans is still unknown. Visuospatial attention represents an optimal model for addressing this issue, since attentional resources are continuously allocated to given spatial locations in order to approach, or avoid, relevant stimuli in the environment (Corbetta & Shulman, 2002).

In the present study, we investigated whether odor pleasantness may rapidly bias visuospatial attention. Specifically, we investigated whether attention shifts closer or further away from visual stimuli that have been previously associated with pleasant or unpleasant olfactory cues. Participants were trained to associate a certain visual shape with a certain odor (e.g., pleasant or unpleasant). Critically, before and after the associative training, participants were required to bisect horizontal lines flanked by the same shapes. The line bisection is, indeed, a standard task extensively employed to assess the allocation of visuospatial attention, in which participants are asked to estimate the apparent midpoint of the line. Healthy individuals from Western cultures typically show a slight but systematic leftward bias, known as pseudoneglect (Bowers & Heilman, 1980; see Jewell & McCourt, 2000, for a review) that is supposed to reflect a strict coupling between right-hemisphere dominance in spatial attention and reading habits (see **Chapter 3**). Nevertheless, situational requirements may also rapidly shift visuospatial attention (see **Chapter 5**). Accordingly, in the recent years some studies have exploited the bisection task as a suitable method for investigating approach and avoidance behaviors (Armaghani, Crucian & Heilman, 2014; Cattaneo, Lega, Boehringer, Gallucci, Girelli & Carbon, 2014; Nash, Mcgregor & Inzlicht, 2010; but see Leggett, Thomas & Nicholls, 2015). On these grounds, here we aimed to explore whether the estimated midpoint would be influenced by the previous olfactory experience associated with each shape. We predicted that, if spatial attention is involved in approaching or avoiding odors according to their pleasantness, the subjective midpoint should be shifted away from the visual stimulus associated with the unpleasant odor, and towards the visual stimulus associated with the pleasant odor. These results would therefore also favor the view that visuospatial attention can be modulated by situational factors, represented here by learned contingent odor-object associations.

6.2. METHODS

Participants

The study, ethically approved by the University of Milano-Bicocca, included 39 right-handed (Oldfield, 1971) students (*M* age=24.9±5.4 years; 30 females). None of the participants reported any stable or temporary deficit of olfaction and none had any history of neurological disease.

Apparatus and procedure

The experiment was run on an Acer Aspire 1350 (15-inch, refresh rate 60 Hz), with participants seated 60 cm from the screen. The experiment consisted of four sequential phases, outlined below (see **Figure 6.1**), that were repeated in two distinct daily-sessions separated by an interval ranging between 4 and 7 days. In a first daily-session, participants were trained uniquely with the pleasant odor, whereas in a second daily-session they were trained uniquely with the unpleasant odor (order of presentation counterbalanced). During the learning phase, odors were presented by means of a custom-built computer-controlled olfactometer.

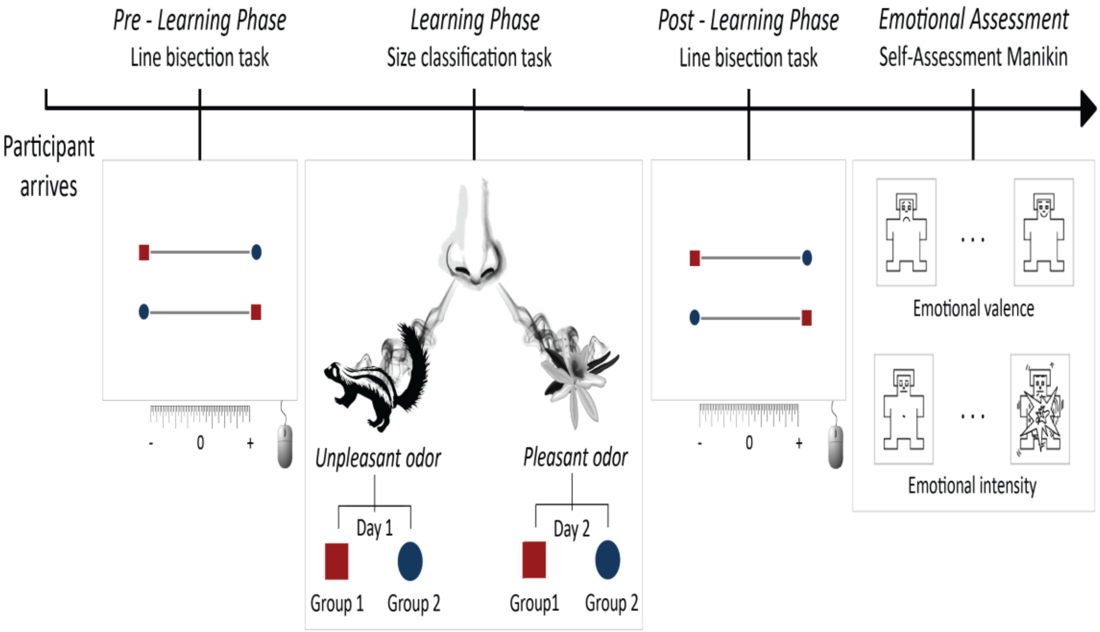

Figure 6.1. Outline of study design. The experiment consisted of four sequential phases, repeated in two daily-sessions. On day 1, participants first completed a computerized line bisection task, in which they had to estimate the midpoint of a line, flanked by different shapes (*Pre-learning phase*). Subsequently, they performed a size-classification task with geometrical shapes (e.g., red square) (*Learning phase*); critically, during the task, the geometrical shape was presented together with a given odor (e.g., pleasant odor), so that participants were trained to specific shape/odor associations. Subsequently, participants performed once again the line bisection task (*Post -learning phase*). Finally, emotional level of pleasure and arousal was assessed through the Self-Assessment Manikin (*Emotional assessment*). Participants were exposed to the pleasant and unpleasant odors in two different daily sessions. Hence, the same participants trained with the red square/pleasant odor association additionally completed a second session, on day 2, in which they were trained to associate the red square with the unpleasant odor. Half of the participants (*N*=20) were trained to associated the odors (pleasant/unpleasant) with the red square, whereas the other half (*N*=19) with the blue circle.

Pre-learning phase. Participants performed a computerized line bisection task. Each trial was composed by a black line. The line was flanked by two visual shapes, placed at a distance of 7 pixels from each end of the line. A red square (side: 60 pixels) and a blue circle (diameter: 60 pixels) were used as flankers. In particular, two different flanker displays were presented: *a)* lines with the red square located at the left end and the blue circle at the right, and *b)* lines with the blue circle located at the left end and the red square at the right (see Fig. 1).

In order to increase stimulus variability line length and line position were systematically varied: two different line lengths (333 pixels and 499 pixels) appeared at eight different spatial positions on the screen. Specifically, lines were always displaced 50 pixels to the left or right of the center and could appear in four different vertical positions (from the centre, displaced 50 or 100 pixels up or down). Long and short lines appeared an equal number of times in each of the eight possible positions. Since line length and line position were not designed as experimental manipulations, they were not analyzed.

The pre-learning phase started with 5 practice trials and consisted of 32 trials. Before starting the experiment, participants were instructed to indicate the line midpoint using the computer mouse. The mouse cursor was a vertical arrow that moved along the horizontal axis only, appearing for an equal number of times at the left or the right extreme of the line, four pixels below the stimulus, on trial onset. Participants indicated the line midpoint by clicking the mouse with the right hand.

Learning phase. In the learning phase participants performed a size-classification task. Participants were first presented simultaneously with two shapes, one big (180 pixels wide) and one small (90 pixels wide), to be used as references. At the beginning of each trial, a fixation point was presented at the center of the screen for a variable time (250, 350, 450 ms), in order to avoid automatic responses. The fixation point was followed by a visual shape (i.e., the target stimulus), that remained on the screen until the participant’s response, and ended with a blank screen lasting for 1000 ms before the next trial. Participants classified the target stimulus as small or large by pressing the (Q) or (P) keys of a vertically aligned keyboard, in order to avoid any right/left directional interference. For the first group of participants (*N*=20) the target stimulus consisted of a big (side: 180 pixels) or a small (side: 90 pixels) red square, while for the other group of participants (*N*=19) it consisted of a big (diameter: 180 pixels) or a small (diameter: 90 pixels) blue circle[1]. Simultaneous with the onset of the fixation point, an olfactory stimulus was presented, which lasted until the presentation of the next fixation point. The olfactory stimuli were provided by Agieffe International® (Milan, Italy) and were presented birhinally to avoid any effect of hemispheric

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[1] This design was chosen in order to compensate for the known association between visual shapes and odor pleasantness (Deroy, Crisinel & Spence, 2013). In particular, while unpleasant odors are usually associated with more angular and sharper shapes, pleasant odors are generally associated with more circular ones (Hanson-Vaux, Crisinel & Spence, 2013). Thus, the present design allowed us to focus on the effect of odor pleasantness.

dominance. In particular, vanilla odor was used as pleasant stimulus (commercial name, *vanilla*), whereas civet odor (commercial name, *zibet*) was used as unpleasant stimulus. Pleasant and unpleasant odors were administered in two separate sessions, in a counterbalanced order across participants. Hence, the first group of participants was trained to associated the red square both with the pleasant (e.g., day 1) and the unpleasant odor (e.g., day 2; order counterbalanced across participants). Similarly, the second group of participants was trained to associate the blue circle with the pleasant and the unpleasant odors in two different daily-sessions. In order to limit the occurrence of habituation on presentation of frequent unpleasant stimuli and, consequentially, reduce their emotional salience (Croy et al., 2013), olfactory cues were presented once every two target stimuli. A total of 36 trials were presented (18 for each stimulus size).

Post-learning phase. The post-learning phase was a line bisection task, identical to the pre-learning phase.

Emotional assessment. The participants' olfactory experience, in terms of pleasure and arousal, was assessed using the 9-point scale of the Self-Assessment Manikin (SAM; Bradely & Lang, 1994).

Data analysis

First, an analysis on reaction times (RTs) to the target stimulus in the learning phase was performed. More specifically, the mean RT to the stimuli presented without any olfactory cues was subtracted from the mean RT of the stimuli presented simultaneously with the olfactory cues (i.e., Δ RTs). Thus, a negative Δ indicates faster responses to targets presented simultaneously with odors than targets presented alone, whereas a positive Δ indicates slower responses.

Second, the bias in line bisection was computed, by subtracting the veridical midpoint from the participants' estimated midpoint. These values were then converted to signed percentage scores, by dividing the true half-length of the interval from the response bias and multiplying the quotient by 100. This procedure yielded a positive score if the participant's response was to the right of the veridical mid-point and a negative score if the response was to the left of it. Since the trained flanker (i.e., red square for the first group, blue circle for the second group) was placed at the left or right line end in the different line conditions, we converted all the response biases so that the trained flanker was arbitrarily considered as to be always placed at the left end. Finally, in order to explore any systematic visuospatial attentional shift after the training, the mean bisection bias in the pre-learning phase was subtracted from that of the post-learning phase (i.e., Δ Spatial bias). Consequently, a negative Δ indicates that the subjective midpoint was shifted toward the trained flanker, whereas a positive Δ that it was shifted away from the trained flanker.

Finally, we performed an analysis on the 9-point scale of the SAM, for the pleasure (1=positive; 9=negative) and arousal (1=low; 9=high) assessment. Furthermore, we also explored the relationship between the visuospatial and the emotional response.

6.3. RESULTS

Response time. Only correct responses to target stimuli (accuracy: 98%) in the learning phase were considered in the analyses. A paired samples *t*-test revealed that Δ RTs to targets presented with the pleasant odor was significantly different from those presented with the unpleasant odor, *t*(38)=10.672, *p*<.001, Cohen's *d*=1.268. Subsequently, in order to explore whether the Δ RTs to targets presented simultaneously with odors were significantly different than those to targets presented alone, a *t*-test for the Δ RTs average of each odor against the value of zero was carried out. Results showed a significant positive Δ RTs (*M*=23.942*, SD*=46.274) with the pleasant odor (i.e., slower responses when odor was presented), *t*(38)=3.231, *p*=.003, Cohen's *d*=1.047. Contrarily, results showed a significant negative Δ RTs (*M*=-75.571*, SD*=41.007) with the unpleasant odor (i.e., faster responses when odor was presented), *t*(38)=11.509, *p*<.001, Cohen's *d*=3.734 (**Figure 6.2a**).

Visuospatial response. Data with more than 2 SD above the mean were removed from the analyses (4.6%). A first preliminary analysis was carried out to compare the bisection bias in the pre-learning phase of the two sessions. Accordingly, a *t*-test was performed for each of the two different flanker conditions between pre- and post-learning performances in each group. Results showed no significant difference, indicating that participants' visuospatial performance was stable across daily-sessions (all *ps* > .05).

A paired samples *t*-test on the Δ Spatial bias revealed that the subjective midpoint was located differently depending on whether the trained flanker was associated to a pleasant or an unpleasant odor, *t*(38)=5.956, *p*<.001, Cohen's *d*=1.367. Subsequently a *t*-test for the Δ Spatial bias against the value of zero was computed, in order to detect whether the learning phase significantly modulated visuospatial performance. The *t*-test against the value of zero showed that the subjective midpoint was shifted toward the trained flanker associated with the pleasant odor (*M*=-1.089*, SD*=1.055), *t*(38)=6.441, *p*<.001, Cohen's *d*=2.089. Contrarily, the subjective midpoint was shifted away from the trained flanker associated with the unpleasant odor (*M*=.718*, SD*=1.716), *t*(38)=2.612, *p*=.013, Cohen's *d*=.847 (**Figure 6.2b**).

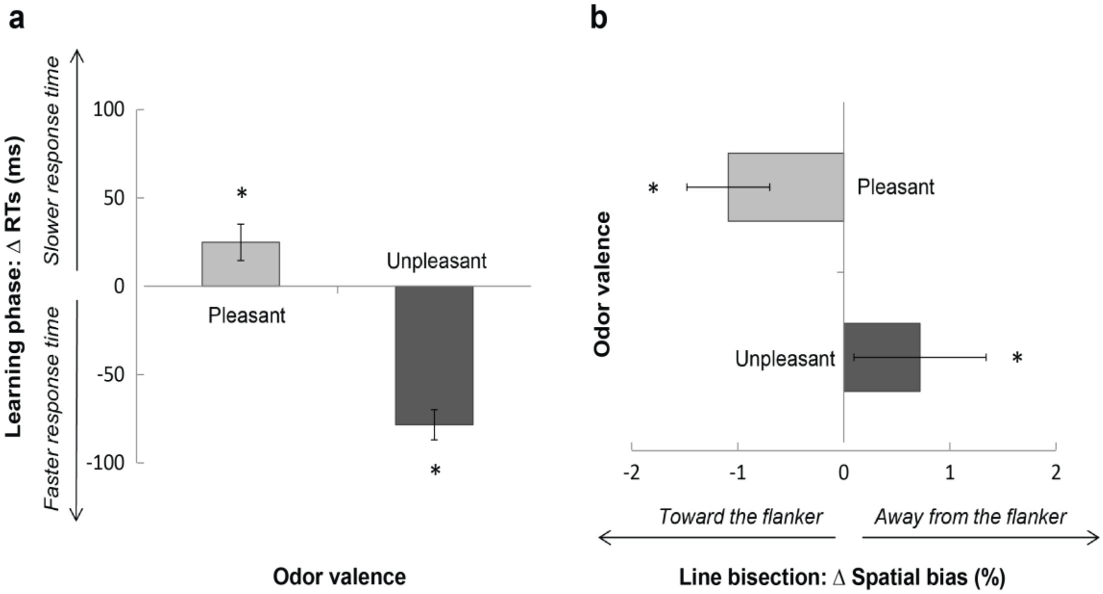

Fig. 6.2. Impact of odor pleasantness on response time (a) and on visuospatial response (b)**.** For the response time, the mean RT to the stimuli presented without any olfactory cues was subtracted from the means RT of the stimuli presented simultaneously with the olfactory cues, to get an index of participants' response time to odor pleasantness (i.e., Δ RTs). Negative Δ RTs indicates faster responses to targets presented simultaneously with odors than targets presented alone and *vice versa* for positive values. Results showed that unpleasant odor elicited faster responses, while pleasant odor elicited slower responses (a). For the visuospatial response, the mean bisection bias in the pre-learning phase was subtracted from that of the post-learning phase (i.e., Δ Spatial bias) to detect any systematic visuospatial attentional shift after the training. Thus, while a negative Δ indicates that the subjective midpoint was shifted toward the trained flanker, a positive Δ indicates that it was moved away from the trained flanker (see the Methods section). Results revealed that participants' estimated midpoint was shifted toward the flanker associated with a pleasant odor, whereas it was shifted away from the flanker associated with an unpleasant odor (b). Error bars ± SEM. **p*<.05.

Emotional response. A paired samples *t*-test on the 9-point scale of the SAM ratings of pleasure showed that the pleasant odor was associated with a more positive rating (*M*=7.1, *SD*=1.1) than the unpleasant odor (*M*=5, *SD*=1.2), *t*(38)=8.486, *p*<.001, Cohen's *d* = 1.769.

Subsequently, a paired samples *t*-test on SAM ratings of arousal showed that the unpleasant odor was associated with a more arousing rating (*M*=3.5, *SD*=1.6) than the pleasant odor (*M*=2.5, *SD*=1.4), *t*(38)=4.221, *p*<.001, Cohen's *d*=.652.

Correlation between visuospatial and emotional response. A Pearson correlation analysis was conducted to analyze the relationship between the SAM ratings of pleasure and the Δ Spatial bias. Results showed that participants who rated the odor as more unpleasant shifted the midpoint more away from the trained flanker, *r*=-.355, *p*=.027. Conversely, no relationship was found for the pleasant odor, *r*=-.077, *p*=.642. Finally, no significant correlation characterized the SAM ratings of arousal and the Δ Spatial (pleasant odor: *r*=.136, *p* =.408; unpleasant odor: *r*=.102, *p* =.538).

6.4. DISCUSSION

The present study explored whether odor pleasantness may influence response time and, more critically, the allocation of attentional resources in the surrounding space. Indeed, pleasant and unpleasant odors are known to induce regulatory reactions at different speed (Bensafi et al., 2002b; Boesveldt et al., 2010). In line with these previous reports, we found that the unpleasant odor was detected faster than the pleasant odor in the learning phase. Notably, since approach and avoidance behaviors often involve a spatial dimension, we investigated whether odor pleasantness may induce selective shifts of visuospatial attention. Results revealed that participants' visuospatial attention clearly deviated according to odor pleasantness. In particular, the subjective midpoint of a line bisection task was shifted away from the visual stimulus associated with the unpleasant odor and towards the visual stimulus associated with the pleasant odor.

Different studies have demonstrated that line bisection performance is modulated by the concurrent presentation of irrelevant lateralized flankers (Cattaneo et al., 2014; de Hevia et al., 2006). For instance, flanker numbers influence the line bisection performance, with a tendency to direct the subjective midpoint toward the larger digit as to balance the numerical disparity between flankers (de Hevia et al., 2006). This means that flanker numbers might act as meaningful bilateral cues. With a similar mechanism, in the present study participants might have classified the shapes as pleasant or unpleasant and, accordingly, placed the subjective midpoint towards the pleasant stimulus as to balance the emotional disparity. More generally, the present results show that situational factors, i.e., rapidly learned contingent crossmodal associations, can influence visuospatial attention (see **Chapter 5**).

Notably, we found that participants who rated the olfactory experience as more negative also shifted their attentional midpoint more away from the stimulus trained with the unpleasant odors, without any correlation with arousal ratings. This may suggest that negative emotional valence, induced by the unpleasant odor, significantly affects the allocation of visuospatial attention. The extent to which the reported effects of odor pleasantness in the line bisection task were determined by an implicit or explicit mechanism cannot be inferred by the present study. Yet, the association with olfactory information modulated the allocation of spatial attention without participants paying voluntary attention to their emotional valence. Indeed, the learning phase was completely irrelevant for the performance of the line bisection task and there was no explicit link in the instruction with the emotional content. Similarly, while in some previous studies the bisection task was followed by a memory test (see Claunch et al., 2012; see also Lichtenstein-Vidne, Henik & Safadi, 2012), here participants were not explicitly required to pay attention to the flankers. In this sense, it is likely that the effects of odor pleasantness on line bisection task were induced by an implicit mechanism. These results are, therefore, in line with previous findings showing that attentional resources can be shifted by irrelevant emotional stimuli (e.g., Cattaneo et al., 2014; Hodsoll, Viding & Lavie, 2011; Tamietto et al., 2005). Nevertheless, future research is needed to clarify whether the effects of odor pleasantness on visuospatial attention is driven by implicit or explicit mechanisms.

Interestingly, the line bisection task has been recently exploited to measure attentional asymmetries linked to motivational states (Nash et al., 2010). In particular, two previous studies explored whether emotional faces placed at the end of the line might alter the allocation of visuospatial attention (Armaghani et al., 2014; Cattaneo et al., 2014). Results of the above studies were partially consistent with the “valence model”, that argues for a left and right hemispheric lateralisation of approach and avoidance behaviors respectively (Davidson, 2003). In fact, a first study by Armaghani et al. (2014) reported a more pronounced leftward bias with lines flanked by two sad faces (i.e., avoidance), whereas a second study by Cattaneo et al. (2014) reported rightward bias with lines flanked by two happy faces (i.e., approach). In turn, our data did not show any lateralised behavior caused by the emotional content of the learning phase. Critically, whereas in the previous studies the same emotional faces (i.e., happy or sad) were presented at both the ends of the line, here only one flanker was trained to be associated with a particular emotional content. This might explain why in our study approach and avoidance were not manifested as a lateralised behavior superimposed by hemispheric dominance, but rather as a flexible change of the allocation of visuospatial resources. Indeed, our findings are consistent with previous reports, in which approach behavior has been shown to produce a decrease in terms of distance between the individual and the target object, whereas avoidance to produce an increase of distance (Strack & Deutsch, 2004). Similarly, in the present study, the learned association between central visual cues and olfactory information biased the performance in a line bisection task, shifting attention away from the stimulus associated with the unpleasant odor and towards the one associated with the pleasant odor. Therefore, these results can be interpreted as a rapid shift of visuospatial attention as a function of situational requirements, i.e., current constraints imposed by the task at hand.

Beyond advancing our understanding of the effects of odors on human behavior, the present research provides original theoretical insights for a more comprehensive evolutionary view of olfaction (Rutherford & Lindell, 2011). Indeed, our findings show that odor pleasantness moves human attention away from the unpleasant source (increase in distance) or close to the pleasant source (decrease in distance). Adopting such a spatial strategy in real-world situations might allow a more efficient exploration of our environment. From an evolutionary perspective, this might be critical in regulating food-seeking and even mate-seeking behaviors: edible food or a fertile mate usually smell pleasant, whereas a poison or a predator smell unpleasant (Yeshurun & Sobel, 2010). Intriguingly, the present findings show that spatial bias can be induced by learned contingent odor-object associations in a very short time. Accordingly, odor pleasantness may quickly create strong spatial boundaries around objects, possibly influencing spatial decision making in perceptual and social contexts (e.g., Spangenberg, Crowley & Henderson, 1996).

In interpreting our results a few limitations need to be carefully considered. First, following previous studies (e.g., Bensafi et al., 2002a) we explored the effect of odor pleasantness by means of two odors, whereas other reports tested crossmodal association with several odors (Boesveldt et al., 2010; see Deroy et al., 2013). Consequently, although the two odors used in our study were selected as representative of being pleasant and unpleasant, future research is needed to generalize the effect of odor pleasantness on visuospatial attention. Second, it is worth noting that the odors used here were not evaluated as equal in terms of pleasantness. Indeed, ratings of pleasure indicated that the unpleasant odor was not *per se* perceived as completely unpleasant. Hence, a more cautious preliminary test on odor pleasantness should be considered in future studies.

To conclude, Don Abbondio and Perpetua felt themselves pushed back by the poisonous smell, while entering in their plague-stricken house. We ourselves encounter unpleasant odors in many everyday life situations and feel such a repulsion, with pleasant odors acting in the opposite way. Here we show that these feelings go beyond their literal meaning: unpleasant odors actually shift away the allocation of spatial attention from the unpleasant source, whereas pleasant sources attract it (see Pool, Brosch, Delplanque & Sander, 2014). This means that odor pleasantness, the primary trait adopted by people to classify and describe odorants (Yeshurun & Sobel, 2010), is a key dimension for the regulation of spatial attention.

CHAPTER 7

Discussion of PART I:

AN INTERACTIVE ACCOUNT OF VISUOSPATIAL ATTENTION

7.1. Summary of the first part of the thesis

The first part of this thesis reports five studies investigating whether prior sensorimotor experience influences the allocation of attentional resources in space.

In particular, in **Chapter 2**, we systematically explored the extent to which the human leftward bias in visuospatial tasks is confined to the near space. Indeed, a left-to-right shift in bisection bias with increasing distance has been largely documented in heathy individuals. This rightward shift of bisection bias has been accounted for by an unbalanced hemispheric processing, with dorsal stream areas on the right hemisphere mainly responsible for coding of near space, and ventral stream areas mainly responsible for coding of far space. In **Chapter 2**, manual and ocular bisections were exploited to further investigate the segregation between near and far space. Participants were required to perform a bisection task of both simple lines and of Judd variants of the Müller-Lyer illusion, presented at three different distances (60, 90, 120cm). Furthermore, since visual lateralized stimuli are mainly processed by the contralateral hemisphere, the spatial location of the lines (left, centre, right) was also manipulated. Results showed that manual bisection of simple lines was modulated by both viewing distance and hemispace of presentation. This pattern was similar for ocular bisection, ruling out possible confounds played by unilateral brain activation in the manual bisection. Critically, the bisection of the Judd illusion, which has been shown to rely on ventral stream areas, was not modulated by viewing distance in either the manual or the ocular conditions. Overall, these findings provide novel evidence supporting the hypothesis that the right hemisphere plays a dominant role in the processing of the space close to the body, though this dominance drastically reduces at farther distances.

In **Chapter 3**, we explored whether the leftward bias in near space is a universal phenomenon. A growing amount of evidence, indeed, confirms the influence of reading and writing habits on visuospatial processing, although this effect has been so far testified mainly as a lateralized shift of a single behavioral sign (e.g., line bisection), with lack of proof from pure right-to-left readers. In **Chapter 3** we contributed to this issue by analyzing multiple attentional and motor indexes in monolingual Italian (i.e., reading from left-to-right), and monolingual (i.e., reading from right-to-left) and bilingual Israeli participants (i.e., reading from right-to-left in Hebrew but also from left-to-right in English). Participants were administered a computerized standard star cancellation task and a modified version in which English letters and words were replaced by Hebrew ones. Tasks were presented on a graphics tablet, allowing recording of both chronometric and spatial parameters. Results showed that reading direction modulated the on-line visuomotor performance from the beginning to the end of the task. Additionally, the spatial bias observed in a computerized line bisection task was also related to the participants' habitual reading direction. Overall, the results favor an interaction between cultural factors, associated to directional scanning, and biological factors, such as hemispheric specialization, in modulating visuospatial processing.

Subsequently, in **Chapter 4**, we further assessed the possible impact of cultural practices on visuospatial asymmetry. In particular, we aimed at exploring the influence of schooling on visuospatial attention in a cancellation task, by testing Western children before and after exposure to formal reading and writing practices. Results indicated that the exposure to formal education exerts a strong influence on the visual search behavior, from the starting position to the online oriented path and the overall distribution of attentional resources during cancellation task. Indeed, a leftward shift of attention in the cancellation of the first target and a preference for orienting left-to-right the visual search, were both incremental from preschoolers to second graders. These findings, therefore, substantiate previous evidence indicating that the orientation of spatial attention shifts leftward over the course of elementary school years, as children learn to read and write in a left-right reading culture. More generally, this evidence provides further support to the view that visuospatial asymmetries are the result of an interplay between cultural and biological factors.

We next reasoned that whereas cultural practices might play a critical role in directing attention in a neutral visual scene, in many other situations attention might also be malleable and sensitive to situational cues. Hence, in **Chapter 5**, the performance of three groups with different reading habits was compared on three ad-hoc versions of the cancellation task: one composed by geometrical shapes, one by Latin letters and one by Hebrew letters. Results showed that participants adapted their habitual visual search, reflecting the expertise in reading habits, depending on situational requirements. Specifically, monolingual participants followed a more lateralized search in the alphabetical compared to the geometrical version of the task. More critically, the visuospatial performance in the bilingual group dissociated depending on whether participants were searching for Hebrew or Latin letters. These findings indicate that visuospatial performance depends on a strict interplay between habitual scanning habits and situational requirements imposed by the task at hand.

Finally, in **Chapter 6**, we explored the possible effects induced by a contingent crossmodal association between odors and visual shapes, and thus by situational factors, on the allocation of visuospatial attention. The prompt recognition of pleasant and unpleasant odors is, indeed, a crucial regulatory and adaptive need of humans. Answers to unpleasant odors ensure survival in many threatening situations. Notably, although humans typically react to certain odors by modulating their distance from the olfactory source, the effect of odor pleasantness over the orienting of visuospatial attention is still unknown. To address this issue, we first rapidly trained participants to associate visual shapes with pleasant and unpleasant odors and then we assessed the impact of this association on a visuospatial task. We found that the use of trained shapes as flankers modulated visuospatial performance in a line bisection task. Specifically, the estimated midpoint was shifted away from the visual shape associated with the unpleasant odor, whereas it was moved towards the shape associated with the pleasant odor. This finding demonstrates that odor pleasantness selectively shifts human attention in the surrounding space and highlight the capability of our attentional system to adapt as a function of current constraints imposed by the task at hand.

Overall, these studies suggest that biological factors (i.e., hemispheric specialization) may interplay with both cultural (i.e., directional scanning associated with language processing) and situational factors (i.e., current constraints imposed by task demands) in modulating visuospatial attention, likely under a hierarchical relationship.

7.2. An *Interactive Account* of *Visuospatial Attention*

One of the longstanding issues addressed by scientists is the nature/nurture debate, concerning the relative contribution of biological and cultural factors to human behavior. Unfortunately, however, in the last century most of the studies focused on the unidirectional link from neural functioning to human behavior. A clear-cut example of this “biological neuroscience” approach can be found in the interpretation of the leftward bias characterizing line bisection in healthy participants, a phenomenon known as pseudoneglect (Bowers & Heilman, 1980). In fact, according to the widely accepted activation-orientation account (Kinsbourne, 1970, 1993; Reuter-Lorenzet al., Moscovitch, 1990), spatial attention is biased to the contralateral hemispace with respect to the most activate hemisphere

(Kinsbourne, 1987). This hemispheric asymmetry, therefore, would be the major factor in giving rise to the visuospatial asymmetry.

Nevertheless, in the last decade increasing attention has been directed to the investigation of neuronal plasticity, i.e., how the brain changes with experience, with various empirical findings supporting the need for a “cultural neuroscience” approach (Ansari, 2012). In fact, cross-cultural studies have shown that human cognitive functions differ markedly across cultures (see for a review, Han & Northoff, 2008). In line with this, reading and writing direction has been found to influence several visuospatial tasks (see **Chapter 3** and **Chapter 4**; see for a review, Chokron et al., 2011), thus challenging the universal interpretation underlying the activation-orientation account (Kinsbourne, 1970). However, if visuospatial biases are interpreted as the direct consequence of hemispheric asymmetries, would it be reasonable to speculate that well-trained directional routines can reinforce these neural biases or even shape them?

A continuously updated circular loop characterizes the relation between brain and behavior (Han & Ma, 2015). Accordingly, cultural experiences and behavioral practices can affect neural structures (Park & Huang, 2010), possibly both at the macrostructural and microstructural levels (Zatorre, Fields & Johansen-Berg, 2012). If we consider that exposure to reading and writing practices implicates the acquisition of specific visuomotor actions at a very early age (i.e., when brain plasticity reaches its highest levels), one may even speculate that this acculturalization may potentially shape anatomical lateralization of visuospatial functions. Indeed, “small educational or cultural differences can lead to broad (and not only exclusively domain-specific) neuronal plasticity” (Ansari, 2012).

Here we propose that the interaction between biological and cultural factors might be linked to neural differences in parieto-frontal connections. Recent evidence on Western participants has shown, in fact, that the lateralization of the middle component of the superior longitudinal fasciculus (SLF II) is highly correlated with the spatial bias observed in a line bisection task (Thiebaut de Schotten et al., 2011). In particular, larger SLF II volumes on the right hemisphere corresponded to a greater leftward deviation in the line bisection. Notably, participants deviating to the right showed an opposite pattern of lateralization (Thiebaut de Schotten et al., 2011). If biases in bisection task are correlated with the lateralization of the SLF II, it might be possible that the behavioral differences observed in Chapter 3 between the three reading groups might be associated with an absent (i.e., bilingual group) or an opposite (i.e., monolingual right-to-left group) lateralization of the SLF II, at least at a group level. Additionally, this complex interaction might be enriched by the influence of biomechanical factors, linked to handedness, especially in tasks that require a stronger motor component (i.e., cancellation task). Nevertheless, **Chapter 5** and **Chapter 6** further showed an impact of situational requirements on the visuospatial performance. These findings, therefore, favor the view that attentional biases induced by culture are malleable and sensitive to external cues (Oyserman et al., 2009). Indeed, participants adapted their typical performance to current constraints, exerted by changes in the salience of stimuli presented across the visual scene.

Based on these findings we propose the hypothesis of a hierarchical relationship between biological, cultural and situational factors in orienting attention in space. In particular, biological factors would exert the earlier influence on attentional biases. Indeed, the faster development of the right hemisphere during prenatal and postnatal life would be responsible for the slight advantage in processing the left visual hemifield (see for a review, Jewell & McCourt, 2000), observed in both preverbal infants (e.g., de Hevia, Girelli, Addabbo & Macchi Cassia, 2014) and in non-human animals (Diekamp, Regolin et al., 2005). Later in life, however, this biological tendency would be either reinforced or modulated by directional scanning practices linked to reading habits and, thus, by cultural factors. Indeed, directional sensorimotor experience, induced by the learning of reading and writing practices, would shift attention toward the preferred proportion of the space, possibly also by shaping asymmetries at the biological level. Finally, visuospatial performance would be further constrained by situational requirements, highlighting the flexibility of the human attentional system. We refer to this hypothesis as the *Interactive Account* o*f Visuospatial Attention* (IAVA). Although this hypothesis currently remains underspecified at many levels, we believe that future research is needed to further explore the influence of sensorimotor practice on neuroanatomical asymmetries.

7.3. Clues for acting in near space: open issues for future research

Is there any specific evolutionary reason for the inversion of visuospatial bias with increasing viewing distance, as reported in **Chapter 1**? Brain lateralization and lateralized behavior are often the result of a specific evolutionary route (Vallortigara & Rogers,. 2005). We suggest, therefore, that a possible reason for the slight advantage of the left visual space close to the body might originate from the impact of cultural practices on human evolution and development. Indeed, one of the major cultural routines that sculpts our brain is reading. Reading is governed by strict spatiotemporal rules that orient our oculomotor system through specific habitual directions, which bias the allocation of visuospatial attention (for a review see Chokron et al., 2011). As soon as children learn to read from right-to-left they show opposite biases (i.e., rightward) compared to children who learn to read in the opposite direction, with this tendency reinforced through experience across the life-span (see **Chapter 3** and **Chapter 4**). These findings challenge the unique reference to the activation-orientation account, and favor the view of the IAVA, according to which cultural routines impact on predetermined neurobiological asymmetries orienting visuospatial attention to the left side of the space (Rinaldi et al., 2014). With this respect, the reported leftward bias for near space (**Chapter 1**) might originate from the influence of reading and writing routines. Hence, a challenging question for future studies is whether a similar rightward shift of bisection bias with increasing distance should be observed also in monolingual right-to-left readers, who display a rightward bias in near space. It might be possible, indeed, that hemispheric asymmetries might partially reverse depending on reading and writing direction in near but not in far space.

Importantly, pseudoneglect in Western populations has been reported not only for perception, as supported by findings with the landmark task, but also for manual action, as when participants make pointing movement to bisect a line. The leftward bias extension to action might be induced partially by writing routine, as well as by biomechanical factors related to the preferential direction of hand movements when acting in near space (i.e., outward vs. inward hand movements) (Dreman, 1974). Indeed, the preference in performing outward tensor movements than inward flexor movements would increase the bias for left space in right handers participants (Dreman, 1974). Hence, we propose that both cultural and biomechanical factors would make the left space preferred for action in Western populations. In line with this hypothesis, several studies found that tool use can shape the borders between near and far space (Gamberini et al., 2008; Longo & Lourenco, 2006; see also Berti & Frassinetti, 2000). For instance, whereas the right-to-left shift with increasing distance was observed when participants bisected lines with a laser point, an overall leftward bias was found in both near and far space when a stick was used (Gamberini et al., 2008; Longo & Lourenco, 2006), likely because this latter tool expanded the range of near space (Berti & Frassinetti, 2000). Hence, these results suggest that a leftward preference exists when objects in space can be manipulated (see Gamberini, Carlesso, Seraglia & Craighero, 2013). Interestingly, the transition from near to far space seems to be modulated by natural variability in arm length (Longo & Lourenco, 2007). Indeed, individuals with longer arms show a more gradual shift in line bisection bias with increasing distance than individuals with shorter arms. This may indicate that objects reachability provides a perceptual metric of distance (Witt, Proffitt & Epstein, 2005), yet highlighting the role of prior sensorimotor experience in computing actual estimates of space.

PART II: THE SENSE OF TIME

CHAPTER 8

A HELPING HAND PUTTING IN ORDER:

Visuomotor routines organize ordered sequences in space

Chapter adapted from:
Rinaldi, L., Di Luca, S., Henik, A., & Girelli, L. (*under review*). A helping hand putting in order: Visuomotor routines organize numerical and non-numerical sequences in space.

8.1. INTRODUCTION

Over the last years, the contribution of the sensorimotor system to human cognition has been largely documented by compelling empirical evidence. In the light of the so called "embodied cognition", according to which cognitive processes are deeply shaped by the body interaction with the environment (Barsalou, 2008; Gibbs, 2006; Wilson, 2002), many authors have suggested an influence of the motor system not only on action control, but also on high-level cognitive functions, such as language (Glenberg & Kaschak, 2002) and mathematics (Andres, Olivier & Badets, 2008; Lakoff & Nunez, 2000). Correspondingly, although mental arithmetic was for long considered a manipulation of abstract symbols, increasing evidence has shown the influence of the sensorimotor system on the mental representation of numerical information. In particular, developmental, behavioral and neuroanatomical findings support the contribution of finger counting to numerical representation, with fingers that might represent the "missing tool" from a rough number sense to a symbolical number concept (Andres, Di Luca & Pesenti, 2008; see also Michaux, Pesenti, Badets, Di Luca & Andres, 2010).

8.1.1. Turning around ordered information

Sound evidence supports the existence of a tight connection between numbers and space. In particular, the "SNARC" (Spatial Numerical Association of Response Codes) effect, referring to faster responses to smaller/larger numerosities with the left/right hand in Western populations (Dehaene et al., 1993), has been taken as a proof supporting the spatial representation of numbers along a "Mental Number Line" (MNL) (Dehaene, 1992; see for a review de Hevia, Vallar & Girelli, 2008). Nevertheless, ordinal sequences are more widely associated to space, since response-side effect have been reported also for non-numerical ordinal information (Gevers, Reynvoet & Fias, 2003, 2004; Gevers et al., 2010). Consequently, the SNARC effect has been partially attributed to the activation of the ordinal meaning of numbers (Gevers et al., 2003). Indeed, processing the position of a number in a sequence, rather than its relevant magnitude, is a sufficient condition to observe the well-known compatibility effect between numbers and space (see van Dijck & Fias, 2011; see for a proposal that distinguishes spatial-numerical associations in terms of cardinality and ordinality, Patro, Nuerk, Cress & Haman, 2015: see **Chapter 1**). Critically, while the spatial nature of the representation of any ordinal sequences is not questioned, the origin of this spatial mapping is still controversial.

On the one hand, some studies have suggested that these compatibility effects originate from reading and writing practices (Dehaene et al., 1993; Berch, Foley, Hill & Ryan, 1999), with a reduced or reversed SNARC effect in right-to-left readers (Dehaene et al., 1993; Zebian, 2005). Indeed, oculomotor routines involved in reading and writing processes would result, through repetition, in a preferential scanning direction of the external space (see Rinaldi et al., 2014) and, in turn, of the internal representational space (Dehaene et al., 1993). Accordingly, specific cultural practices seem to be strictly necessary for a numerical mapping along a spatial continuum (Núñez, 2011; Núñez, Cooperrider & Wassmann, 2012; see for a review McCrink & Opfer, 2014; see also Nuerk et al., 2015).

On the other hand, some studies have attributed to these practices a relative rather than an absolute importance (Fischer et al., 2010; Shaki & Fischer, 2012; Shaki et al., 2009), since the directional scanning associated to reading habits can flexibly impact on the SNARC effect (Fischer et al., 2009; Fischer et al., 2010). For instance, manipulating the position of digits within a text (i.e., placing them from left-to-right or from right-to-left) can influence the typical response-side compatibility effect, suggesting that the impact of reading habits is far from being persistent (Fischer et al., 2010; see also Patro, Fischer, Nuerk & Cress, 2015). Moreover, the presence of spatial-numerical associations in preschool-age children speaks in favor of observational learning, rather than formal reading practices, as critical to shape the internal organization of mental representation (Ebersbach, Luwel & Verschaffel, 2015; Hoffmann, Hornung, Martin & Schiltz, 2013; Opfer, Thompson & Furlong, 2010; Patro & Haman, 2012; Shaki, Fischer & Göbel, 2012). This evidence complements those on nonhumans (Drucker & Brannon, 2014; Rugani, Vallortigara, Priftis & Regolin, 2015) and on infants (Bulf, de Hevia & Macchi Cassia, 2015; de Hevia et al., 2014), speaking in favor of an early onset of spatial-numerical associations (see for a discussion de Hevia, Girelli & Macchi Cassia, 2012).

Only recently, however, some authors proposed that fingers might represent an embodied tool onto which numbers are mapped in space (Di Luca & Pesenti, 2011; Fischer & Brugger, 2011; but see for a more generalized concept of numerical embodied representation, Moeller, Fischer, Link, Wasner, Huber, Cress & Nuerk, 2012). In particular, associations between numbers and space can be determined by finger counting routines (Di Luca, Granà, Semenza, Seron & Pesenti, 2006) or, at least, can be modulated by them (Fischer, 2008; Fischer & Brugger, 2011; Riello & Rusconi, 2011; but see Brozzoli, Ishihara, Gobel, Salemme, Rossetti & Farné, 2008; Plaisier & Smeets, 2011). This ordered practice, indeed, would establish a preferential direction for mapping numerical information on the hand space (see for a discussion, Cohen, Naparstek & Henik, 2014). Accordingly, number-to-finger associations have been shown to influence number processing (Di Luca & Pesenti, 2008; Sato, Cattaneo, Rizzolatti & Gallese, 2007; Domahs, Klein, Moeller, Nuerk, Yoon & Willmes, 2011) and to modulate mental numerical representation (Di Luca et al., 2006; Di Luca, Lefèvre & Pesenti, 2010; Fischer, 2008; Domahs, Moeller, Huber, Willmes & Nuerk, 2010). Moreover, the link between finger counting and number processing is further strengthened by neuroimaging evidence showing that activation of the primary hand motor cortex in numerical processing is partially modulated by the direction of finger counting (Tschentscher, Hauk, Fischer & Pulvermüller, 2012). On these grounds, Fischer and Brugger (2011) proposed that spatial-numerical associations might originate from finger counting routines. Whether the starting point and the directionality of finger counting is related to handedness or to cultural factors (Bender & Beller, 2011d; 2012; Lindemann, Alipour & Fischer, 2011; Knudsen, Fischer & Aschersleben, 2014), however, is still a matter of debate (see for a discussion Previtali, Rinaldi & Girelli, 2011).

In summary, the assumption that finger counting can shape, together with reading habits, the spatial representation of ordinal sequences receives general consensus. Nevertheless, up to date no study has directly compared the influence of finger counting and reading direction. In fact, previous researches investigated the strength of finger counting routine on MNL representation (Brozzoli et al., 2008; Di Luca et al., 2006; Riello & Rusconi, 2011) without considering language direction.

8.1.2. Combining directions: The present study

The literature supports finger counting and reading habits as determinant cultural visuomotor routines for representing ordinal information in space. However, no study has so far investigated whether the spatial representation of numbers and, more generally, of ordinal sequences relies on finger counting (FC), on reading direction (RD) or on an interplay of both. In the present study we directly explored the strength of the “finger-representation account” and of the “reading-representation account” in a series of three experiments, by requiring participants to map ordinal information to all fingers of the dominant hand. Moreover, to emphasize the impact of reading direction on the spatial representation of ordinal information, Israeli participants reading both from left-to-right and from right-to-left were involved.

In Experiment 1 we tested whether Spatial-Numerical Associations (SNAs) are determined by FC direction or by the standard Western left-to-right orientation of the MNL[1]. In particular, participants performed a finger-mapping compatibility task with Arabic numbers, with the direction of the finger-digit mapping that was systematically varied from left-to-right or from right-to-left (i.e., 1 to 5: thumb-little finger vs. little finger-thumb). Additionally, to test the strength of FC account we further manipulated the direction of the mapping, by requiring participants to perform the task with their right hand in both pronated and supinated posture. In Experiment 2, we explored whether SNAs on the hand space are determined by FC or by RD. Specifically, we investigated whether SNAs might adapt flexibly to situational factors, by requiring participants to map number words, presented both in English and in Hebrew, to specific fingers. Finally, we investigated the role of FC and RD in the mapping of non-numerical ordinal information, i.e., days of the week, presented in both languages. Thus, in all experiments, we explored the spatial representation of ordinal information on the hand space, i.e., on fingers.

In Experiment 1 we hypothesized that if fingers are associated to specific numbers through long-term memory representations, responses should be faster when numbers are mapped according to participants' FC routine, independently from hand posture and from the standard orientation of the MNL. Indeed, finger-numeral representations are particularly emphasized in the current task setting, which requires a fine discrimination between all fingers of the dominant hand at the response level. Similarly, in Experiment 2, number words should be preferentially mapped according to participants' FC routine regardless of language direction, due to long-term memory finger-number associations. These patterns of results would therefore suggest that finger-number associations are not sensitive to the direction of the cultural reading and writing habit, leading to the same response pattern in both prone and supine postures. Finally, since the mapping of non-numerical ordinal information has been shown to be modulated by RD, and since the present task setting particularly emphasizes FC, we expect both routines to contribute to the preferential spatial mapping. This hypothesis was tested in experiment 3.

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[1] A recent study by Shaki & Gevers (2011) found a regular SNARC effect with Arabic numbers in bilingual Israeli participants. On these grounds, in the present paper we refer to the MNL as flowing from left-to-right.

8.2. EXPERIMENT 1

In Experiment 1 participants performed a finger-number mapping compatibility task with Arabic numbers in palm-up and in palm-down postures (Di Luca et al. 2006; *Experiment 2*). However, while Di Luca and colleagues (2006) adopted a ten-fingers response setting, emphasizing both directions within and between hands, in the present study we specifically focused on numerosity 1-to-5, by requiring participants to map numbers to fingers of their right dominant hand only. In fact, a recent study by Riello and Rusconi (2011) tested the relation between MNL and FC representations by means of a unimanual classification tasks (i.e., two fingers of the same hand used to respond in different postures). Faster RTs were found only when directions of the two representations were compatible (i.e., when the right hand is pronated or the left hand is supinated, since both FC and RD run from thumb-to-little fingers and thus from left-to-right). Riello and Rusconi (2011) suggested that this pattern might have been driven by the existence of two vectors (MNL and FC) having similar force but opposing direction. Furthermore, they attributed the difference between their own and Di Luca et al.'s results (2006) to the response setting greatly differing in terms of finger discrimination. It remains to be established whether unimanual responses might reduce the influence of FC routine (see Riello & Rusconi, 2011). Hence, in Experiment 1, we opted for a unimanual task but where all five fingers were involved. Following the study of Di Luca et al.'s (2006), we predicted that FC would determine the preferential spatial representation of numbers.

8.2.1. METHODS

Participants

A total of 20 right-handed participants took part in Experiment 1 for payment (*M* age=24.7 y.o., *SD*=1.4; 13 females). Participants were Israeli students from the Ben-Gurion University of the Negev (Israel). All of them were native-born Israelis with Hebrew as their mother language and with good English skills: they were all familiar with a left-to-right language, since they started to learn English in the fourth/fifth grade of primary school (Arabic digits are typically written from left-to-right in Hebrew). They also judged themselves as fluent in the second language and therefore we considered them altogether as bilingual or bidirectional participants. Laterality was further assessed by means of the Edinburgh Inventory (Oldfield, 1971): all participants were classified as right-handers. All the participants had a normal or corrected-to-normal visual acuity and were naïve with respect to the experimental hypotheses.

Apparatus

Data collection and stimulus presentation were controlled by a Dell OptiPlex 760 vPro computer with an Intel Core 2 duo processor E8400 3 GHz. The stimuli were presented on a Dell E198PF 19" LCD monitor. Participants were seated approximately 60 cm from the screen and answers were given by key presses on a standard QWERTY keyboard. More specifically, participants adopted a typical typing position on the keyboard to ensure a comfortable posture for the hand and arm and a good inline positioning of the fingers (keys H, J, K, L), except for the thumbs, which was lowered slightly (key B). All the non-responding keys were removed from the keyboard to facilitate fingers movement. For the palm-up posture condition, the keyboard was turned upside-down and was fixed on the table. The left, non-responding, hand was always placed on the ipsilateral knee, with the same posture of the hand used to execute the task.

Stimuli and Procedure

Stimuli were Arabic digits from 1 to 5, presented in black Times New Roman font (size 36) at the centre of a white background screen. Each trial started with a central cross lasting for a variable time (500, 650, 800, 950 and 1100 ms), in order to avoid automatic responses, followed by the stimulus that remained on the screen until the participant answered, and ended with a blank screen lasting for 500 ms before the next trial (see **Figure 8.1a**).

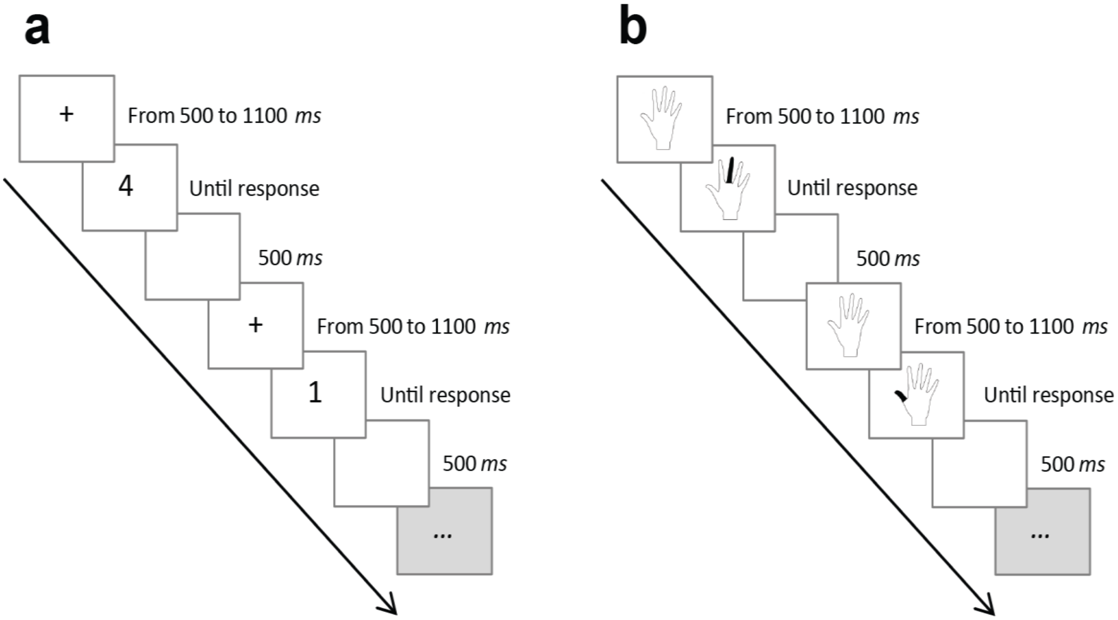

Figure 8.1. Procedure of Experiment 1 for (a) the experimental block with numbers and for (b) the motor baseline task. During the experimental block, each trial started with a fixation point, followed by a number that lasted on the screen till participant's answer, and ended with a blank screen. Similarly, in the motor baseline, an hand silhouette with a darkened finger appeared on the screen till participant's answer.

Each mapping was presented in a separated block, in a counterbalanced order across participants. Four mappings were obtained combining 2 variables (see **Figure 8.2b**): *a)* numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb) and *b)* hand posture (prone, supine). Thus, in the prone condition mapping A consisted in associating 1 to the thumb and 5 to the little finger, and mapping B, in associating 5 to the thumb and 1 to the little finger. Likewise, in the supine condition we had mapping C, associating 1 to the thumb and 5 to the little finger, and mapping D, associating 5 to the thumb and 1 to the little finger. Mappings resulted, therefore, as completely compatible (A) or incompatible (B) with both participants FC and MNL orientations, whereas mapping C and D were only compatible with the FC or MNL, respectively. The four mappings were assigned in a counterbalanced order across participants. A block was composed of 10 (not analyzed) practice and 50 experimental trials. The order of presentation of the stimuli was pseudorandomly determined (at least three items before the repetition of the same digit). Participants had to press, as fast as possible, the key corresponding to the displayed digit as indicated by the specific finger-digit mapping; during the training phase, a figure showing the finger-digit mapping to be adopted was placed beside the keyboard to help participants remembering each association.

Critically, Riello and Rusconi (2011) manipulated hand posture (i.e., prone and supine) across participants, in order to minimize errors due to mental rotation strategies (e.g., see Leuthard, Bächtold & Brugger, 2005). In our study, however, we reduced variability due to the individual differences, by assessing each posture in two different daily-sessions to all participants (e.g., between 24 and 72 hours).

To control for possible motor speed differences between fingers and hand postures, at the end of each session participants performed a motor baseline reaction time task. Stimuli were line drawings of a right hand in a prone or supine posture. Each trial started with a drawing of a hand lasting for a variable time (500, 650, 800, 950 and 1100 ms), in order to avoid automatic responses. It was followed by the same drawing with a finger pseudorandomly darkened, that remained on the screen until the participant answered with the corresponding finger, and then ended with a blank screen lasting for 500 ms before the next trial started (see **Figure 8.1b**). This task was composed of 10 (not analyzed) practice and 50 experimental trials.

Finally, at the end of the second session, we assessed the personal finger counting strategy as in Di Luca et al.'s study (2006). Participants were asked to place their hands palm down on their knees and, then, to show "how they count from 1 to 10 on their fingers". A spontaneous finger counting assessment allowed us to better focus on the embodied level of finger counting routine (see Wasner, Moeller, Fischer & Nuerk, 2014; see also Lucidi & Thevenot, 2014).

Finger counting assessment

Overall, 18 participants out of 20 started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand. Two subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 18 participants (*M* age=23.9 y.o., *SD*=1.3; 12 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check possible differences in the motor baseline task. The overall error rate was 2.6% for the prone posture and 2.3% for the supine posture. A 2x5 repeated measures analysis of variance (ANOVA) on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Results showed a main effect of finger, *F*(4, 68)=14.17, *p*<.001, η^2_p=.47 (thumb: *M*=430.67 ms, *SD*=47.3; index finger: *M*=414.3 ms, *SD*=51.8; middle finger: *M*=426.6 ms, *SD*=55.6; ring finger: *M*=448 ms, *SD*=57; little finger: *M*=424.5 ms, *SD*=50.9). A main effect of hand posture was also found, *F*(1, 17)=15.48, *p*<.002, η^2_p=.49, with faster RTs for the prone condition (prone posture: *M*=414.3 ms, *SD*=51; supine posture: *M*=443.4 ms, *SD*=51.7), while the interaction was not significant. To avoid any possible confounding motor effects, we first calculated for each participant the average RT of each finger in each posture. Then, the RT of the fastest finger was subtracted from the RT of each other finger, obtaining an index of each finger relative speed (i.e., finger Δ). The finger Δ was then subtracted from the average RT of each finger in each experimental mapping, resulting in a corrected finger RT. A further correction was applied to avoid confounding effects of hand posture. Due to the faster performance in the prone posture, for each participant the average RT of each finger in the prone posture was subtracted from its average RT in the supine posture (i.e., posture Δ). The posture Δ was then subtracted from the average RT of each finger in each experimental mapping of the supine posture, resulting in a corrected supine finger RT. Only RTs of correct responses were analyzed in the experimental sessions and we separately performed an analysis of errors.

8.2.2. RESULTS

Errors

Error rates were respectively 3.2% (A), 3.3 % (B), 2.8% (C), 3.1% (D) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A repeated measures ANOVA 2x2 analysis with numbers direction (thumb-little finger, little finger-thumb – referred to 1-5 finger-association) and hand posture (prone, supine) as within-subjects variables was carried out. Results showed no significant main effect or interaction.

Reaction Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (3.4% of the data). A repeated measures ANOVA 2x2 with numbers direction (thumb-little finger, little finger-thumb) and hand posture (prone, supine) as within-subjects variables was carried out. A significant effect of numbers direction was found, *F*(1, 17)=32.65, *p*<.001, η^2_p=.66, with faster RTs for the thumb-little finger mappings, i.e., mappings A and C (*M*=508.5 ms, *SD*=125), compared to little finger-thumb mappings, i.e., B and D (*M*=563.2 ms, *SD*=133.7) (see **Figure 8.2a**). All the other effects were not significant.

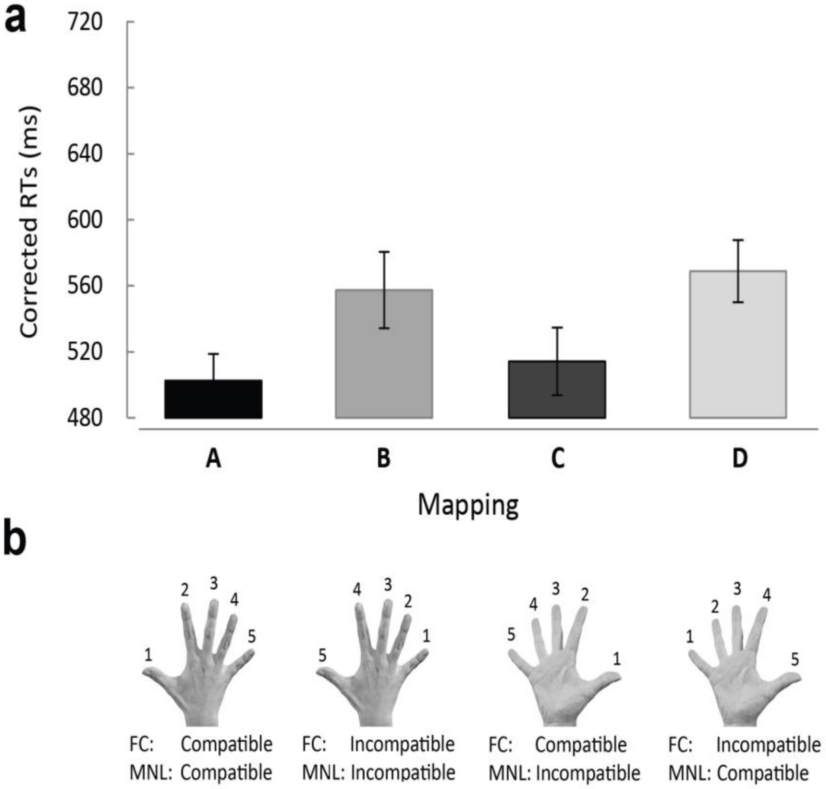

Figure 8.2. (a) Results of Experiment 1. Mean corrected response times (RTs), as a function of the finger-digits mappings. Results showed that participants responded faster with mappings compatible with FC (i.e., mappings A and C). Error bars indicate ±1 standard error of the mean. (b) Finger-digit mappings of Experiment 1. Mappings were obtained by combining two variables: a) numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb) and b) hand posture (prone, supine). In this way, we aimed at exploring whether Arabic digits are preferentially mapped according to FC, MNL or to a combination of both. Thus, in mapping A both FC and MNL were compatible, while in mapping B they were both incompatible. In mapping C only FC was compatible, while in mapping D only MNL was compatible.

8.2.3. DISCUSSION

The aim of Experiment 1 was to assess the strength of FC account on SNAs, by requiring participants to identify Arabic digits from 1 to 5. In particular, according to our hypothesis, the fastest mapping was found when participants mapped numbers congruently to their finger counting strategy (i.e., mappings A and C), independently from the orientation of the MNL compatibility. Thus, our findings extended Di Luca et al.'s study (2006) to unimanual responses, based on responses given with all fingers of the hand (cf. Riello and Rusconi, 2011, in which only the index and middle fingers were used).

A previous study by Di Luca et al. (2006), indeed, found that when all 10 fingers are used to respond, the mapping reflecting the prototypical finger-counting strategy led to faster reaction times than the mapping congruent to the space-based representation, i.e., a left-to-right oriented MNL. However, Brozzoli et al. (2008) further showed that irrelevant numbers influenced a tactile detection task in a way compatible only with the MNL representation. These apparently contrasting results maybe attributed to different experimental methods leading to different activation of the finger-space representation. Indeed, while in Brozzoli et al.'s study (2008) participants answered to a tactile stimulus delivered to a finger with a foot pedal response (i.e., passive task), here a finger motor response was required (i.e., active task). These differences might have modulated the competition between MNL and FC representations, likely resulting in higher competition when fingers representation is crucial to the selection of the response (see for a discussion also Riello & Rusconi, 2011).

8.3. EXPERIMENT 2

In Experiment 2 we addressed whether SNAs are determined by FC, by RD or by an interplay of both. Participants were now required to map both English and Hebrew number words to fingers of their right hand. In other words, Experiment 2 explored whether language direction might influence the finger-number mapping found in Experiment 1. In fact, previous research has shown that SNAs in bilingual participants rely on language manipulation (Fischer et al., 2009, 2010; Shaki & Gevers, 2011). For instance, the orientation of SNAs rapidly changes depending on whether participants are processing Russian or Hebrew number words in a classic bimanual classification task (Fischer et al., 2009). In Experiment 2 we explored any effect of language manipulation in the mapping of Hebrew and English number words on the hand space. We hypothesized that, if fingers are associated to specific numbers through long-term memory representations consolidated by visuomotor practice across the life-span, language constraints should not influence SNAs.

8.3.1. METHODS

Participants

A total of 24 right-handed participants (*M* age=24.3 y.o., *SD*=1.5; 12 females) took part in Experiment 2 for payment. Participants were bilingual Israeli students from the Ben-Gurion University of the Negev (Israel).

Apparatus

We used the same apparatus as in Experiment 1.

Stimuli and Procedure

Stimuli consisted of English number words (ONE, TWO, THREE, FOUR, FIVE) and Hebrew number words (אחת, שתים, שלוש, ארבע, חמש). The procedure was the same as the one adopted in Experiment 1. Eight mappings were obtained combining 3 variables: *a)* numbers direction, referred to ONE-FIVE finger-association (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language of the stimuli (English, Hebrew). Thus, with English number words, in the prone condition mapping A consisted in associating ONE to the thumb and FIVE to the little finger, while mapping B in associating FIVE to the thumb and ONE to the little finger. Likewise, in the supine condition we had mapping C associating ONE to the thumb and FIVE to the little finger, and mapping D associating FIVE to the thumb and ONE to the little finger. Therefore, in the English condition, mappings resulted as completely compatible (A) or incompatible (B) with FC and RD, whereas mapping C and D were only compatible with the FC or RD, respectively. The same mappings were also obtained for Hebrew number words. A description of the English and Hebrew mappings is reported in **Figure 8.3**. As in Experiment 1, hand posture was assessed in two separated daily sessions. Moreover, mappings of the same language were assessed subsequently within the same session. Hence, in Experiment 2 participants had to complete four different blocks in each session (e.g., day one: A-B-E-F; day two: C-D-G-H). The order of the eight mappings was counterbalanced across participants. To control for possible motor speed differences among fingers and hand posture, participants performed a baseline reaction time task for each pronated and supinated posture, as in Experiment 1.

Finally, at the end of the second session the personal finger counting strategy was assessed.

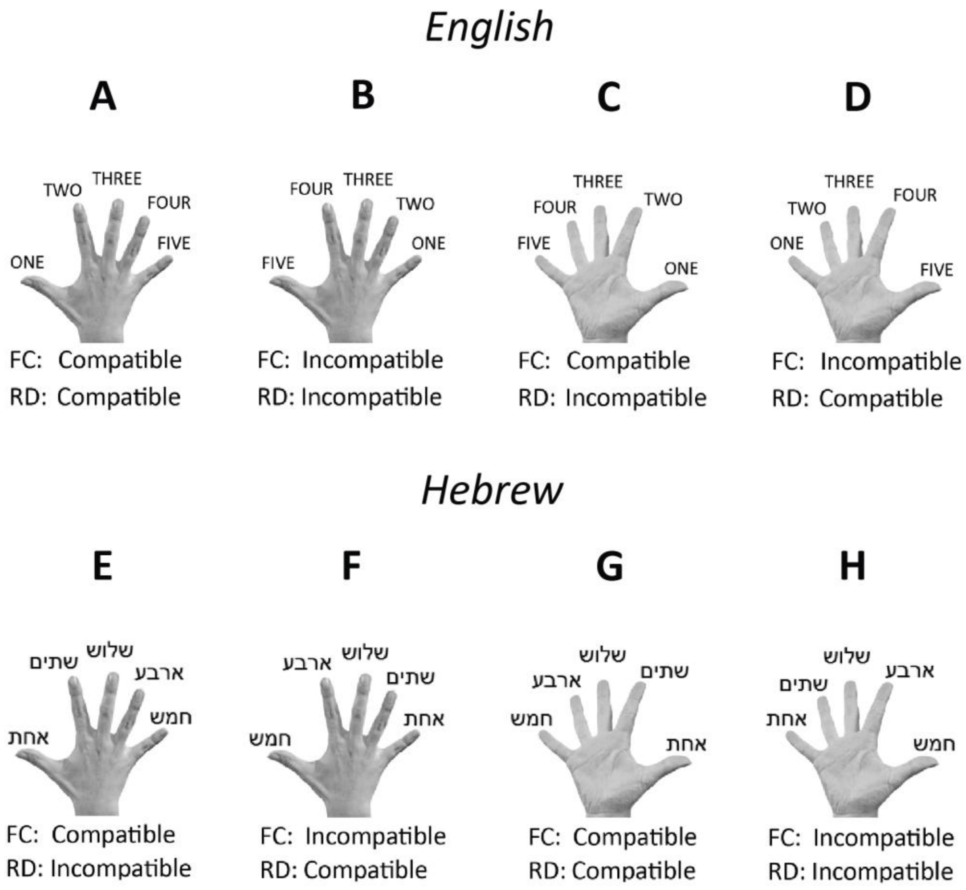

Figure 8.3. Finger-number words mappings of Experiment 2. Mappings were obtained by combining three variables: *a)* numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language of the stimuli (English, Hebrew). In this way, we aimed at explore whether number words are preferentially mapped according to FC, RD or to a combination of both.

Finger counting assessment

Overall, 21 participants, out of 24, started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand. Three subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 21 participants (*M* age=23.9 y.o., *SD*=1.3; 12 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check for possible motor differences in the baseline task. A repeated measures 2x5 ANOVA on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Similar to Experiment 1 finger and hand posture were both found to be significant. Thus, as in Experiment 1, only corrected RTs were analyzed.

8.3.2. RESULTS

Errors

Error rates were respectively 3.1% (A), 3.9 % (B), 4.1% (C), 2.5% (D) 5.2% (E), 4.5 % (F), 2.8% (G), 4% (H) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A repeated measures ANOVA 2x2x2 with numbers direction (thumb-little finger, little finger-thumb – referred to 1-5 finger-association), hand posture (prone, supine) and language (Hebrew, English) as within-subjects variables was carried out. Results showed no main effect or interaction.

Reaction Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (4.6% of the data from the English mappings and 4% of the data from the Hebrew mappings). A repeated measures ANOVA 2x2x2 with numbers direction (thumb-little finger, little finger-thumb), hand posture (prone, supine) and language (Hebrew, English) as within-subjects variables was carried out. Results revealed a significant effect of language, *F*(1, 20)=95.28, *p*<.001, η^2_p=.83, with faster RTs for Hebrew number words (*M*=550.8 ms, *SD*=92.2) compared to English ones (*M*=605.7 ms, SD=84.8). Most importantly, a significant effect of numbers direction was found, *F*(1, 20)=39.84, *p*<.001, η^2_p=.67, with faster RTs for the mappings compatible with FC (*M* = 558.6 ms, *SD* = 82.4; i.e., mappings A, C, E, G) compared to the non-compatible ones (*M*=597.9 ms, *SD*=91.9; see 3a) (see **Figure 8.4**). Finally, a significant interaction between numbers direction and hand posture was found, *F*(1, 20)=9.12, *p*<.01, η^2_p=.31. Post-Hoc comparisons[2] revealed that, additionally to the main effect of numbers direction, the typical finger counting mapping on the prone condition was significantly faster (*M*=549.2 ms, *SD*=75.5) than the typical finger counting mapping on supine posture (*M*=567.9 ms, *SD*=89.3*; p*<.05). No others main effects or interactions were found.

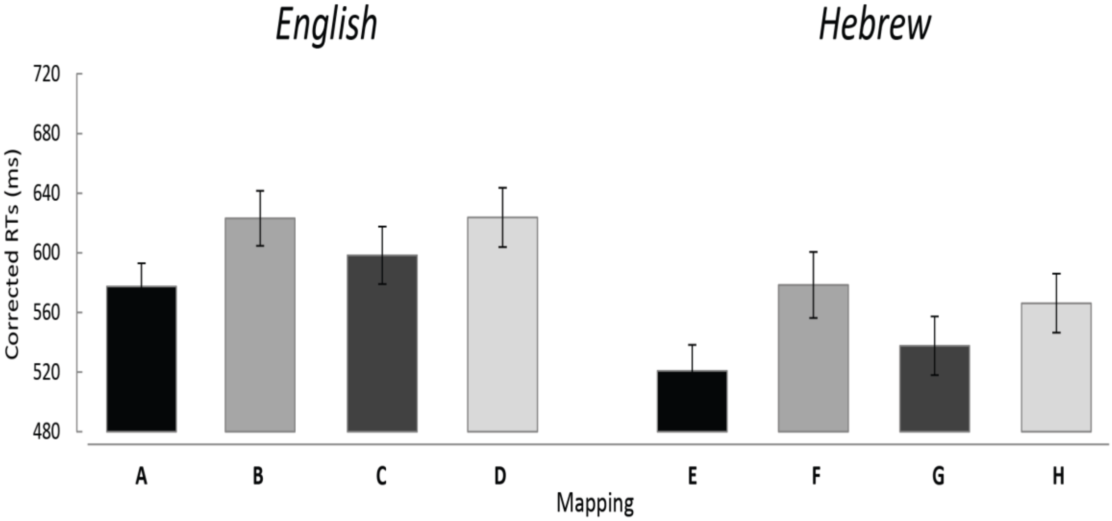

Figure 8.4. Results of Experiment 2. Mean corrected response times (RTs), as a function of the finger-number words mappings both in the English (i.e., mappings A-D) and in the Hebrew conditions (i.e., mappings E-G). Results showed that participants responded faster with mappings compatible with FC, either with English number words (i.e., mappings A and C) or with Hebrew number words (i.e., mappings E and G). Error bars indicate ±1 standard error of the mean.

8.3.3. DISCUSSION

In Experiment 2 we explored whether language direction influences the spatial representation of numbers, by presenting number words either in English or Hebrew. Indeed, it has been previously demonstrated that the spatial representation of numbers can be influenced by either language dependent modifications (Fischer et al., 2009; Shaki & Gevers, 2011) or short-term positional changes (Fischer et al., 2010) in bimanual classification tasks. However, no study has so far investigated whether such flexibility might be observed for SNAs on the hand space. Critically, results of Experiment 2 revealed that

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[2] Scheffè correction was applied in this study to test all the unplanned comparisons with a conservative approach.

SNAs on the hand space (i.e., fingers) are not influenced by language dependent modifications, i.e., the fastest mapping was always compatible with the typical FC strategy. These results give further support to the hypothesis of a long-term memory association between fingers and numbers (see Di Luca & Pesenti, 2011).

8.4. EXPERIMENT 3

In Experiment 3 we investigated whether the mapping of non-numerical ordinal information, i.e., days of the week, presented either in Hebrew or in English, relies on FC, on RD or on a combination of both. In fact, in Experiments 1 and 2 no effect of language emerged, contrary to previous studies that adopted a bimanual task setting (e.g., Fischer et al., 2009; Shaki & Gevers, 2011). This preferential mapping can be accounted for by the influence of participants' previous experience with finger counting. Finger counting routine, indeed, would consolidate a systematic association between a specific finger and a specific ordinal position of the numerical sequence. To test the role of FC routine in the mapping of non-numerical information we therefore designed Experiment 3. In particular, we hypothesized that both visuomotor routines would influence the representation of non-numerical ordered sequences. Specifically, although days of the week are not systematically mapped onto fingers, we expect this information to be sensitive to both RD and FC. Thus we predict that the fastest mapping should result when both routines are compatibly oriented.

8.4.1. METHODS

Participants

A total of 22 right-handed participants took part in Experiment 3 for payment (*M* age=24.1 y.o., *SD*=2.2; 14 females). Participants were Israeli students from the Ben-Gurion University of the Negev (Israel).

Apparatus

We used the same apparatus as in Experiment 1.

Stimuli and Procedure

Stimuli were English and Hebrew words of the days of the week. Since in Israel the workweek starts on Sunday and ends on Thursday, this ordinal interval was considered in

Experiment 3. Therefore, each stimulus consisted of the English word of the day of the week (SUNDAY, MONDAY, TUESDAY, WEDNESDAY, THURSDAY) and of the corresponding Hebrew word (יום ראשון, יום שני, יום שלישי, יום רביעי, יום חמישי). The procedure was the same as in Experiment 1. Eight mappings were obtained combining 3 variables: *a)* days direction, referred to Sunday-Thursday finger-association (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language (English, Hebrew). Thus, with English days in the prone condition, mapping A consisted in associating SUNDAY to the thumb and THURSDAY to the little finger, while mapping B in associating THURSDAY to the thumb and SUNDAY to the little finger. Likewise, in the supine condition we had mapping C associating SUNDAY to the thumb and THURSDAY to the little finger, and mapping D associating THURSDAY to the thumb and SUNDAY to the little finger. Therefore, in the English condition, mappings resulted as completely compatible (A) or incompatible (B) with FC and RD, whereas mapping C and D were compatible only with the FC or RD, respectively. The same mappings were also obtained for Hebrew days (see **Figure 8.5**). As in Experiment 1, hand posture was assessed in two separated daily sessions. Moreover, mappings of the same language were assessed subsequently within the same session. Hence, as in Experiment 2, participants had to complete four different blocks in each session (e.g., day one: A-B-E-F; day two: C-D-G-H). The order of the eight mappings was counterbalanced across participants. To control for possible motor speed differences among fingers and hand posture, participants performed a baseline reaction time task, as in Experiment 1 and 2.

Finally, at the end of the second session the personal finger counting strategy was assessed.

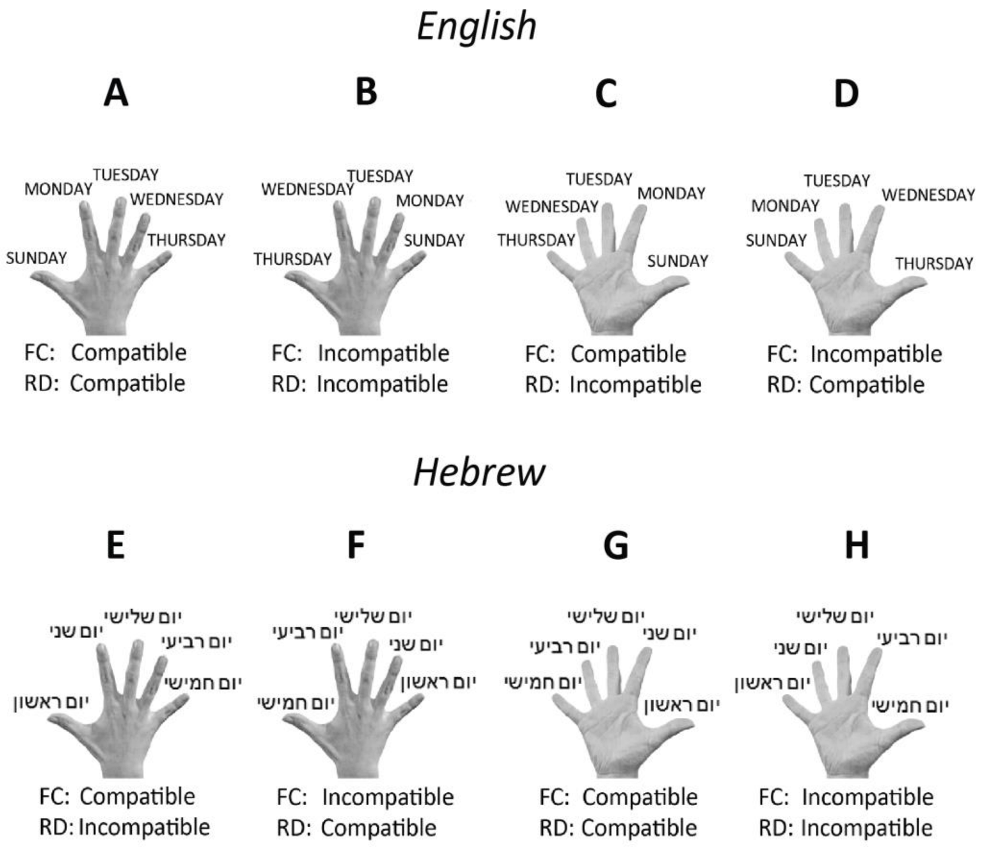

Figure 8.5. Finger-days of the week mappings of Experiment 3. Mappings were obtained by combining three variables: a) days direction, referred to Sunday-Thursday finger-association (thumb-little finger, little finger-thumb), b) hand posture (prone, supine) and c) language (English, Hebrew). In this way, we aimed at explore whether number words are preferentially mapped according to FC, RD or to a combination of both.

Finger counting assessment

Overall, 20 participants, out of 22, started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand. Two subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 20 participants (*M* age = 24 y.o., *SD* = 2.4; 13 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check for possible motor differences in the baseline task. A repeated measures 2x5 ANOVA on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Similar to Experiment 1 and 2, finger and hand posture were both found to be significant, thus, only corrected RTs were analyzed.

8.4.2. RESULTS

Errors

Error rates were respectively 3.4% (A), 2.9 % (B), 4.2% (C), 4.4% (D), 3% (E), 2.9 % (F), 3.5% (G), 3.3% (H) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A repeated measures ANOVA 2x2x2 with days direction (thumb-little finger, little finger-thumb – referred to Sunday-Thursday finger-association), hand posture (prone, supine) and language (English, Hebrew) as within-subjects variables was carried out. Results showed a main effect of language, $F(1, 19)=7.45$, $p<.05$, $\eta^2_p=.28$, with more errors in English (3.7%) than in Hebrew mappings (3.1%). Additionally, a main effect of hand posture was found, $F(1, 19)=6.75$, $p<.05$, $\eta^2_p=.26$, with more errors in the supine posture (3.9%), compared to the prone posture (3.1%). All the others main effects and interactions were not significant.

Response Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (4.2% of the data for the English mappings and 3.9% for the Hebrew mappings). A repeated measures ANOVA 2x2x2 with days direction (thumb-little finger, little finger-thumb), hand posture (prone, supine) and language (English, Hebrew) as within-subjects variables was carried out. Results revealed a significant main effect of language, $F(1, 19)=102.19$, $p<.001$, $\eta^2_p=.84$, with faster RTs for the Hebrew words ($M=566.9$ ms, $SD=62.3$) compared to the English ones ($M=662.4$ ms, $SD=80.7$). Second, a main effect of days direction was found, $F(1, 19)=34.94$, $p<.001$, $\eta^2_p=.65$, with thumb-little finger mappings ($M=602.3$ ms, $SD=82.2$), i.e., those compatible with participants' finger counting strategy, faster than little finger-thumb mappings ($M=627$ ms, $SD=91.6$). Most importantly, the triple interaction was significant, $F(1, 19)=16.69$, $p<.002$, $\eta^2_p=.47$. Post-Hoc comparisons revealed that with English days of the week, mapping A ($M=629.6$ ms, $SD=61.2$) was significantly faster than all the others (B: $M=677.3$ ms, $SD=82.3$; C: $M=665.6$ ms, $SD=79$; D: $M=676.9$ ms, $SD=100.2$; all $ps<.005$), while for the Hebrew days, mapping G ($M=538.5$ ms, $SD=65.3$) was significantly faster than the others (E: *M*=575.6 ms, *SD*=61.7; F: *M*=571.1 ms, *SD*=60; H: *M*=582.8 ms, *SD*=62.2; all *ps*<.005). Note that in mappings A and G, FC and RD were both compatible (see **Figure 8.6**). All the others main effects and interactions were not significant.

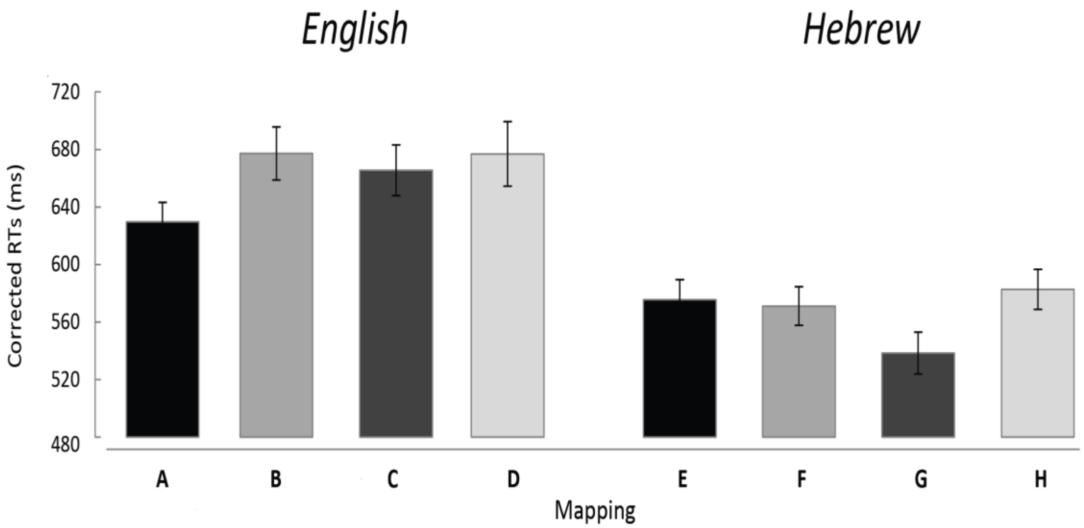

Figure 8.6*.* Results of Experiment 3. Mean corrected response times (RTs), as a function of the finger-digits of the week mappings both in the English (i.e., mappings A-D) and in the Hebrew conditions (I.e., mappings E-G). Results showed that participants responded faster when both FC and RD were compatible (i.e., mapping A with English words and mapping G with Hebrew words). Error bars indicate ±1 standard error of the mean.

8.4.3. DISCUSSION

In Experiment 3 we explored whether the spatial mapping of non-numerical ordinal information relies *a)* on FC, *b)* on RD or *c)* on a combination of both. Results showed that the preferential mapping resulted when both FC and RD routines were compatible, thus supporting the alternative *c)*. While previous investigations with bilingual participants showed an impact of language direction on the spatial representation of ordinal information in bilingual participants (Shaki & Gevers, 2011), the present study shows that also FC contributes to shape this spatial representation. Indeed, participants responded faster in A than in all the other mappings with the English days, while they responded faster in G with the Hebrew days. Altogether, these results show that both FC and RD play a critical role in the spatial representation of non-numerical ordinal information. More specifically, these results indicate that the representation of non-numerical ordinal sequences on the hand space relies on multiple visuomotor routines.

8.5. GENERAL DISCUSSION

Robust evidence points to directional visuomotor routines, such as finger counting and reading habit, as relevant for representing ordered information in space. However, no study has so far investigated the routine on which we rely on more. The present study addressed this issue by requiring bilingual participants, reading either from left-to-right or right-to-left, to map ordinal information to all fingers of their right dominant hand. Results of Experiments 1 and 2 show that the spatial representation of numerical information relies mainly on finger counting routine. Moreover, results of Experiment 2 indicate that this representation is not sensitive to the contextual manipulation of the numerical code (Arabic *vs* verbal numerals; Hebrew *vs* English number words), suggesting that it is stored in long-term memory as a consequence of the repeated visuomotor activity throughout the lifespan. Finally, Experiment 3 unveils that the spatial representation of non-numerical ordinal sequences, i.e., days of the week, relies on both finger counting and reading habit. This suggests that when ordinal information is not consolidated with space through a specific visuomotor routine, the most compatible representation is induced by the combination of different experienced directional routines. Overall, the present study shows that the spatial representation of ordinal sequences on the hand space relies on directional routines and, particularly, on finger counting. These findings might have broad implications for current models of numerical representation and, more generally, for an experience-based view of cognition.

8.5.1. Spatial-numerical associations counts on fingers

Recent studies have shown that the spatial representation of numbers can rely on (Di Luca et al., 2006), or at least be influenced by (Fischer, 2008; Fischer & Brugger, 2011; Riello & Rusconi, 2011; but see Brozzoli et al., 2008), the direction of finger counting routine. Using a number-to-finger mapping task, in the present study we show that participants responded faster to Arabic digits and to number words when numerical information was mapped according to participants' finger counting routine. These findings are in line with evidence suggesting a strong influence of finger counting routine on SNAs on the hand space (Di Luca et al., 2006) and, more generally, they provide further evidence for a reliable contribution of FC on the spatial representation of numbers (e.g., Fischer, 2008; Riello &

Rusconi, 2011). However, while Di Luca et al. (2006) reported a predominance of the finger counting mapping over the orientation of the MNL, recently Riello and Rusconi (2011) found that both FC and MNL need to be congruently oriented for generating faster mappings. These apparently contrasting findings, might result from different task settings and from a different emphasis on fingers representation. Indeed, while in the study of Riello and Rusconi (2011) participants were required to classify parity numbers with two fingers only (i.e., thumb and little finger), the present study adopted a five keys response setting resulting in increased finger discriminability. The larger emphasis on the hand space, due to the use of all fingers of the hand, thus might have led to greater contribution of FC.

A current debate in the literature concerns whether the direction followed in finger counting is influenced by cultural factors, such as reading direction, or by biological factors, such as handedness (see, for a discussion, Previtali et al., 2011). Indeed, the finger counting strategy is to a certain degree culturally shared, since young children can observe and learn from their peers how to use fingers for counting (Bender & Beller, 2012). On these grounds, some authors proposed that the visuomotor scanning linked to reading and writing direction might provide a critical cue for the starting point and the overall direction of the finger counting routine (see Lindemann et al., 2011). At the same time, however, also handedness represents a sound candidate for shaping finger counting direction, with previous studies indicating a tight association between the starting hand of FC and hand dominance (see for a discussion Previtali et al., 2011). In a sample of right-handed bidirectional readers we found that more than 80% of participants started to count with the thumb of the right hand and proceeded to the little finger (with the same order followed on the left hand). Critically, this percentage replicates those reported in previous study with a Western population (Di Luca et al., 2006; Sato & Lalain, 2008), without any apparent difference due to cross-cultural variability between the two samples. Therefore, since our participants were all right handers, our findings speak in favor of a critical role of handedness in the starting point of FC and calls into question whether eye scanning associated with reading direction can be an important factor in the origin of FC direction (cf. Lindemann et al., 2011). Indeed, these findings show that RD only partially interacts with FC, establishing the primacy of the latter on the hand mapping of ordinal information. The fact that the preferential mapping of numerical information was not dependent on hand posture and on language direction, provides evidence for a hand-centered representation.

8.5.2. An helping hand putting in order

What makes numbers specials is that they convey different meanings among which the most salient are the cardinal meaning, referring to the numerosity of a set, and the ordinal meaning, indicating the relative position of a certain item within a set. While the former is a unique feature of numbers, the latter is shared with any ordinal sequences, such as the days of the week or the letters of the alphabet. The present study was focused on the spatial representation of ordinal information. Compelling evidence, indeed, supports a common spatial representation for both numerical and non-numerical ordinal sequences (Gevers et al., 2003; 2004; Previtali, de Hevia & Girelli, 2010; Macchi Cassia, Picozzi, Girelli & de Hevia, 2012; Rinaldi, Brugger, Bertolini, Bockisch & Girelli, 2015), even though the origin of this spatial mapping is still debated.

In three experiments, we found that numerical information was preferentially represented according to finger counting routine, while both finger counting and reading direction had to be congruent for generating faster associations for non-numerical ordinal information on fingers. In fact our findings suggest that when the task requires a more fine fingers discrimination at the response level, finger counting plays an active role in the mapping of ordered information. While the impact of finger counting routine on SNAs is rather unsurprising and supported by different findings, the influence of this practice on the representation of non-numerical ordinal sequences may not be taken for granted. In fact, one may question how fingers would be helpful for representing non-numerical ordinal information in space.

We propose that finger counting support to ordinal representation might be grounded on the one-to-one correspondence principle, strengthened by the systematic association between a specific finger and a specific ordinal position during counting. Experienced first with numbers, this mapping might be further easily generalized to any ordinal sequences, through repetition. Therefore, we suggest that finger counting may be considered supportive not only to arithmetic (Crollen & Noël, 2015; see also Rinaldi, Gallucci & Girelli, 2015), but also for the development of ordinal meaning, being fingers an embodied tool available to children to keep track of information in a culturally-shaped order (Wiese, 2003), at least when visual processing is not impaired (Crollen, Noël, Seron, Mahau, Lepore & Collignon, 2014). Future studies are needed to explore this intriguing possibility.

8.5.3. Implications for current models of embodied cognition

Beyond investigating the role of directional routines in the mapping of numerical and non-numerical information in personal space, the present study contributes to a deeper understanding of both embodied and situated factors in the determination of SNAs. Indeed, current views of numerical cognition emphasize the importance of both embodied and situated knowledge (e.g., Fischer, 2012; see also Wasner, Moeller, Fischer & Nuerk, 2014). In particular, according to a recent proposal, three different aspects would account for the flexibility of SNAs (Fischer 2012; see also Fischer & Brugger, 2011). The first one, named as grounded cognition, would reflect universal properties of the physical world, such as the stable associations between numerical information (small/large) and vertical space (bottom/top) that would come from accumulating objects (Ito & Hatta, 2004; Shaki & Fischer, 2012). The second one, named as embodied cognition, would reflect the influence of sensorimotor experience on cognition, such as the effect of reading and writing direction (Zebian et al., 2009) or finger counting (Di Luca et al., 2006; Fischer, 2008) on SNAs. The third one, named as situated cognition, would lastly reflect the influence of current constraints imposed by the task at hand, such as the effects induced by language direction manipulations in bilingual readers on SNAs (Fischer et al., 2009, 2010). Hence, the influence of visuomotor practices in shaping the spatial representation of numbers has been taken as evidence for an embodiment of numerical concepts (Fischer & Brugger, 2011) although situated factors, such as task demands and the specific experimental setting adopted, might in turn influence SNAs (Fischer, 2012). In the present study, we provide novel evidence that might enrich the understanding of both embodied and situated factors on numerical representation.

In particular, Experiments 1 and 2 speak in favor of an embodiment of numerical concepts because the privileged numerical representation was hand-centered, i.e., neither hand posture or language direction counted. Since previous evidence has shown that numerical mapping in bimanual classification tasks is prone to language manipulation (Fischer et al., 2010; Shaki & Gevers, 2011) and yet to situational requirements, the present findings suggest that the mapping on the hand space is not sensitive to such manipulation, as it preferentially corresponds to the individual's prototypical finger-counting. It might be therefore possible that the more we actively use parts of our body in the response setting, the more we rely on inner and bodily representations grounded on an egocentric sensory-motor schema**.** Intrinsic features of finger counting routines would make them resistant to situational requirements. Finger counting routine is indeed practiced early in development, it is reinforced by observational exposure and by self-practice, and it is characterized by an exact one-to-one correspondence between a specific finger and a specific number.

On the contrary, in Experiment 3 a significant influence of situational factors was found. More specifically the privileged mapping of non-numerical ordinal information was determined by a combination of both reading and finger counting direction, thus resulting in an impact of hand posture. Overall, these findings highlight the more flexible representation of non-numerical ordinal sequences, showing how embodied factors interact more generally with situational requirements.

To conclude, we suggest that the need for putting in order multiple information in everyday life makes our cognitive system highly capable of representing abstract ordered information, by adjusting previous directional experience (finger counting, reading direction) to current requirements imposed by the task at hand.

CHAPTER 9

KEEPING AN EYE ON SERIAL ORDER:

Ocular movements bind space and time

Chapter adapted from:
Rinaldi, L., Brugger, P., Bockisch, C. J., Bertolini, G., & Girelli, L. (2015). Keeping an eye on serial order: ocular movements bind space and time. *Cognition*, *142*, 291-298.

9.1. INTRODUCTION

People's ability to maintain and recall the order of events or elements in a sequence is a key function of working memory (WM) (Baddeley, 1992; Lashley, 1951). Among others, this capacity is fundamental to comprehension, learning, and reasoning (Baddeley, 2012). Given its importance in human cognition, over the past years different models have been dedicated to account for memory for serial order. In particular, according to a predominant class of models (i.e., position marking models) the serial order within WM would follow from the pairing of items with some external representation of their location within the sequence (e.g., Brown, Preece & Hulme, 2000; Henson, 1998), rather than from a mere pairing between the items themselves (e.g., Lewandowsky & Murdock, 1989). In the wake of the position marking models, Abrahamse and colleagues (Abrahamse, van Dijck, Majerus & Fias, 2014) recently claimed that serial order would be grounded on the spatial attention system. More specifically, the position of ordered elements to be remembered would be translated into internal spatial coordinates and, thus, into a spatial representation (Abrahamse et al., 2014). Importantly, the manipulation of this serial order representation would engage spatial attention resources and, in turn, retrieval of memorized items would result from a selection operated by spatial attention mechanisms (Abrahamse et al., 2014).

According to this hypothesis, recent evidence has shown that serially-ordered verbal information is encoded along a spatial dimension (Previtali et al., 2010; van Dijck & Fias, 2011) and that covert spatial attentional resources are recruited to access to this serial order representation (van Dijck et al., 2013; see **Chapter 1**). In particular, short sequences of numbers and words memorized in WM were found to be associated to space: items presented at the beginning of the memorized sequence were responded to faster with the left hand-side, while items from the end were responded to faster with the right hand-side (van Dijck & Fias, 2011). Moreover, retrieving an item from an ordered sequence has been shown to be mediated by covert spatial attention (van Dijck et al., 2013), since the detection of a visual target appearing in the left or in the right side of the space was modulated by the serial position of a previous memorized item acting as a prime. Specifically, the later the position of an item in the memorized sequence, the faster the detection of the target in the right side of the space (van Dijck et al., 2013, 2014). The functional involvement of spatial processing in serial order was confirmed in a recent study where retrieval was found to be facilitated by visuospatial priming and, more specifically, by task-irrelevant exogenous spatial cues (De Belder et al., 2014).

Similar space-time interactions have been also described for overlearned temporal information (Ouellet et al., 2010; Santiago et al., 2007; Torralbo et al., 2006; Weger & Pratt, 2008), supporting more generally the view that temporal order is represented along a spatial continuum (see **Chapter 1**). According to these spatio-temporal interactions, parietal and frontal cortex largely involved in attention control, participate in memory for order information (Koenigs, Barbey, Postle & Grafman, 2009; Marshuetz, 2005; Marshuetz & Smith, 2006). A tight connection between space and time, indeed, pervades our daily experience. Events occur at a certain time and in a certain spatial context throughout life. As time is less graspable than space, temporal concepts are grounded in spatial experience (Torralbo et al., 2006; for review see Bonato et al., 2012). Hence, we frequently borrow from the language of space when describing duration ("a short break") or event location ("in the distant past"), and we make use of related words to indicate the order of events ("before”) in both spatial and temporal contexts.

However, although attention can move in space covertly, i.e., without eye movements, or overtly, with eye movements (Posner, 1980), this distinction has been widely challenged by recent findings indicating that also covert attentional processes are tightly linked to oculomotor processes (Corbetta, 1998; Corneil & Munoz, 2014; Engbert & Kliegl, 2003). Yet, evidence supporting overt spatial attention in mediating between space and serial order is still missing. Indeed, while previous studies have shown that covert spatial attention is engaged in accessing the serial representation, there is no direct proof of sensorimotor changes in overt orienting during serial processing. This is an important omission, since earlier reports already suggested a possible involvement of spontaneous oculomotor strategies in the processing of ordered verbal information (Robertson, 1990; Weinberg, Diller, Gerstman & Schulman, 1972). In the present study, we therefore hypothesized that the scanning of a serial representation would be accompanied by spontaneous eye movements. This hypothesis was based on two main observations. First, recent findings have shown that the scanning of an internal representation goes along with a concurrent sensorimotor scanning (e.g., Loetscher, Bockisch & Brugger, 2008; Loetscher, Bockisch, Nicholls & Brugger, 2010). These studies hark back to the general idea that oculomotor processes involved in visual scanning are also crucial for the mental scanning of visual images (Hebb, 1968). Second, and more importantly, the left-to-right orientation of the serial representation might be grounded on sensorimotor mechanisms and, more specifically, on reading and writing practices (Abrahamse et al., 2014). Indeed, oculomotor routines involved in both reading and writing would result, through repetition, in a preferential directional scanning of the external space (see Rinaldi et al., 2014). This directional preference would be reinforced in Western populations, where reading occurs from left-to-right, by the slight leftward bias in visuospatial attention processing (Bowers & Heilman, 1980; see Abrahamse et al., 2014; de Hevia et al., 2012). On these grounds, we hypothesized that, if serial order is grounded on sensorimotor processes, eye movements concurrent to the retrieval of ordered information should reflect the internal scanning of its spatial representation.

To address this issue, we conducted a three-phase study. In the first phase, five random digits (sampled from the range 1-10), i.e., the positive set, presented sequentially at the center of the screen had to be memorized in correct order by participants. In the second phase, all digits from 1 to 10 were randomly presented twice at the central position and participants had to decide whether a digit, i.e., the probe, was a member of the positive set or not (“recognition”). In this phase, we thus adopted a fixed-set procedure, with the same positive set that was tested for multiple trials (Sternberg, 1966; 1975). Finally, participants repeated the memorized sequence (“recall”). Participants were required to respond verbally in both the recognition and the recall phases. Importantly, to investigate the role of the oculomotor system in mediating between space and serial order, we measured spontaneous eye movements at the onset of the verbal response.

In the recognition phase, we first predicted that reaction times should vary as a function of the item’s serial position in the memorized sequence. Specifically, lower reaction times should characterize the recognition of the serially first and last items, showing the presence of a primacy and a recency effect, respectively (Corballis, 1967). This hypothesis was based on the assumptions of the Start-End Model for serial order (Henson, 1998b), according to which the encoding of order information consists in the storage of episodic tokens that incorporate positional representations in a specific spatiotemporal context. More precisely, this positional coding assumes that the first and the last items of a sequence are the most salient elements (Henson, 1998b). Accordingly, various studies have found faster responses for serially-presented first and last items (e.g., Burrows & Osaka, 1971; Corballis, 1967; Corballis, Kirby & Miller, 1972). Despite a long-standing debate on the presence of primacy and recency effects, contrasting results are widely accounted for by methodological differences (see Sternberg, 1969; see also McElree & Dosher, 1989).

Second, and critically, if overt spatial attention mediates the search and the retrieval of serially-ordered items, eye movements should also unveil the presence of primacy and recency effects. This should be reflected by a greater involvement of overt attentional resources, i.e., larger eye movements, for the middle items. Indeed, since there is possible representational overlap between middle items (Henson, 1998b), the search and the retrieval of these elements would be more demanding, i.e., requiring more visuospatial attentional resources. Contrarily, the first and last items would represent respectively the leftmost and the rightmost endpoint of the spatial array and their search would, consequently, require less attentional orienting. Since serial order is represented along a horizontal plane (Abrahamse et al., 2014; see also Bonato et al., 2012), we hypothesized that accessing to such a representation should be mediated mainly by horizontal eye movements. Furthermore, according to recent findings (van Dijck et al., 2013; 2014), we also explored whether the recognition of the first element would induce a leftward overt attentional shift, while the recognition of the last element would induce a rightward shift.

Finally, if serial information is spatially encoded in a left-to-right format, eye position during recall should correspondingly deviate more to the right, the later the item position in the sequence. The systematic involvement of oculomotor mechanisms during sequence recall would support the hypothesis that serial order is grounded on visuospatial attention. Indeed, scattered evidence for the spatial representation of serial order was already collected by Harcum (1975). More recently, it has been inferred from a dichotomous response-setting, i.e., response time differences between left and right responses to memorized items (van Dijck & Fias, 2011), or from a dichotomous visual-setting (van Dijck et al., 2013; 2014), i.e., response time difference to lateral targets primed by memorized items. Thus, a possible left-to-right shift of eye position during recall would provide the first direct evidence that memorized items are ordered in a continuous space.

9.2. METHODS

Participants

Ten right-handed participants (7 women), aged between 26 and 37, participated in the study. Right handedness was established using the Edinburgh handedness test (Oldfield, 1971). None of the participants were on medication. The sample size (*N*=10) was based on normative sample sizes used in the literature on similar topics (Loetscher et al., 2008; Loetscher et al., 2010).

Apparatus

Stimuli were projected on a large screen (220x220 cm). Matlab software (Mathworks, Natick, MA; release 2008b) was used for programming, presentation of stimuli, and timing operations. Both verbal responses and eye movements were collected. The participants' spoken responses were recorded from a microphone using LabVIEW software (National Instruments, Austin, Texas) and were synchronized offline with eye position.

Eye tracking

Horizontal and vertical eye movements were recorded at 220 Hz with a head-mounted video-oculography (VOG) device ("EyeSeeCam"; Schneider, Dera, Bard, Bardins, Boening & Brand, 2005), consisting of swimming goggles with two mounted infrared cameras. A model of the eye rotation is used by the VOG system to derive the horizontal eye position from the pupil position recorded in the coordinate system of the cameras. An additional offline calibration was performed to improve the accuracy. Eye position was calibrated at the beginning and midway through the experiment by asking subjects to look at a sequence of 5 fixation points (at 0° and ±9.5° horizontally and vertically). We then fitted a linear function to the fixation position (in camera coordinates) to the sine of the target eccentricity.

Procedure and design

Participants were seated comfortably at a viewing distance of approximately 70 cm from the large screen. They performed the three phases of the study with their head movements minimized through a chin rest. Participants were required to memorize a sequence of five digits in correct order, during a first phase ("sequence presentation"; see **Figure 9.1a**). Following the presentation of the positive set, a 2*s* period elapsed, allowing rehearsal. In a second phase ("recognition"), all digits ranging from 1 to 10 were randomly presented twice. Participants were instructed to verbally say "*Yes*" or "*No*", depending on whether the item presented did or did not belong to the memorized sequence (see Figure **9.1b**). Finally, they were required to verbally repeat the memorized sequence (third phase, "recall"; see **Figure 9.1c**). Eighteen different sequences were presented in a counterbalanced order across participants. All blocks, in which the correct sequence was not correctly repeated in the recall phase, were not included in the analysis. The sequence was however presented once again in an extra block at the end of the experiment. Between each block, a short break of 30*s* was included, after which a new positive set was presented on the screen.

The experimenter signaled verbally the beginning of each block. Furthermore, a longer break of 300*s* was included after participants performed the first half of the blocks. Only correct responses to the memorized digits were analyzed.

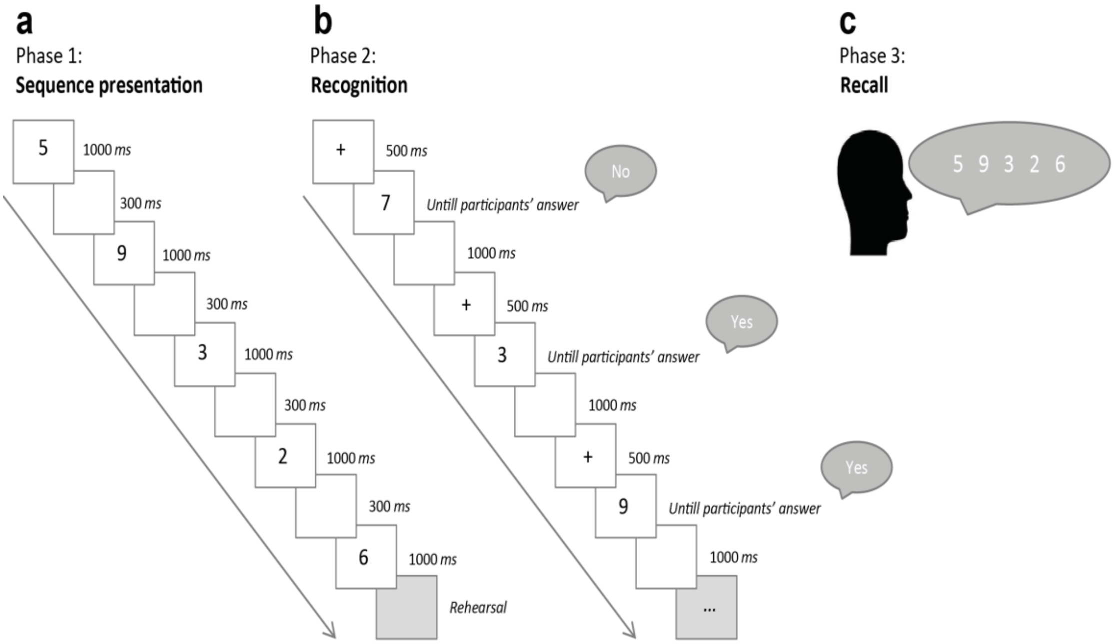

Figure 9.1. The three phases of the study: (a) the presentation of the sequence of five digits to be memorized in correct order; (b) the recognition phase, in which participants had to recognize whether the number presented belonged to the memorized sequence or not; (c) the recall phase, in which participants had to verbally repeat the memorized sequence.

9.3. RESULTS

For each trial we computed both reaction times (RTs) and eye position (EP). RTs indicate the time elapsed between the onset of the digit presentation and the onset of the verbal response (recognition phase). EP was recorded in both the second and the third phase. Specifically, during the recognition phase, the change in EP was measured during the decision-making interval and was computed as the difference between the EP at the onset of the verbal response and EP at the onset of the digit presentation. Accordingly, we computed an absolute EP (ignoring the directional value of eye movements) to explore the overall involvement of overt attentional resources, with respect to digit serial position. Moreover, we computed a directional EP, where negative values indicated a leftward change, while positive values a rightward change. During the recall phase, EP was registered at the onset of the each verbal response, and analyzed as a function of the serial position of the pronounced digit.

All the analyses were performed through linear mixed models (LMM). RTs or EP were used in different analyses as the dependent variable, including subject as a random factor. Serial position (SP: 1, 2, 3, 4, 5) was included as a fixed factor. We used the Linear Mixed Models procedure in SPSS 21.0 to analyze the data.

Recognition phase

During the recognition phase, only correct responses (96%) to the memorized digits were analyzed. Analyses were computed for *1)* RTs, *2)* absolute horizontal EP, *3)* absolute vertical EP, *4)* directional horizontal EP, and *5)* directional vertical EP. Serial position (SP: 1, 2, 3, 4, 5) was included in all the analyses as a fixed factor[1].

Recognition phase: Reaction Times

Only trials from the memorized sequences with an accurate recall in the third phase (on average, 16.5 of 18 sequences) and correct positive trials (accuracy was 93% and 94% for the positive and negative set respectively) were considered in the analyses. The mean RT was 1020 ms (*SD*=183).

In the recognition task, a main effect of SP on RTs was found, *F*(4, 1518.11)=3.96, *p*<.005. In particular, the first serial position was characterized by lower RTs (all *p*s<.05) indicating, overall, the presence of a primacy effect. Although not significant, results also indicated a slight advantage for recognizing the item presented last in time (see **Figure 9.2**). **Table 9.1** shows the fixed effects comparisons between the five levels of SP.

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[1] When the digits' numerical magnitude (Small: 1-5; Large: 6-10) was included in the analyses, no significant main effect or interaction with SP was found to be significant.

Table 9.1. Fixed effects comparisons, with Bonferroni corrections, between the five levels of serial position (SP), for reaction times (RTs). Means (ms) and standard errors, in parentheses, are reported along the diagonal for each SP. Parameter estimates for fixed effects and *t*-test results are reported for all comparisons.

RTs	**SP 1**	**SP 2**	**SP 3**	**SP 4**	**SP 5**
SP 1	***M*=975** *(13.8)*	*b*=.057 *[.021; .095]* $t_{1518.02}$=3.08 *p*<.005	*b*=.065 *[.028; .102]* $t_{1518.05}$=3.47 *p*<.002	*b*=.057 *[.021; .094]* $t_{1518.09}$ = 3.09 *p*<.005	*b*=.044 *[.007; .081]* $t_{1518.17}$=2.3 *p*<.02
SP 2		***M*=1033** *(15.3)*	*b*=.007 *[-.03; .044]* $t_{1518.07}$=.37 *p* = .7	*b*=-.0005 *[-.037; .036]* $t_{1518.04}$=-.025 *p* = .98	*b*=-.015 *[-.052; .024]* $t_{1518.09}$=-.74 *p* = .45
SP 3			***M*=1040** *(14.7)*	*b*=-.008 *[-.044; .029]* $t_{1518.09}$=-.4 *p*=.69	*b*=-.021 *[-.059; .016]* $t_{1518.26}$=-1.1 *p*=.27
SP 4				***M*=1037** *(14.7)*	*b*=-.014 *[-.051; .024]* $t_{1518.18}$=-.72 *p*=.47
SP 5					***M*=1013** *(13.5)*

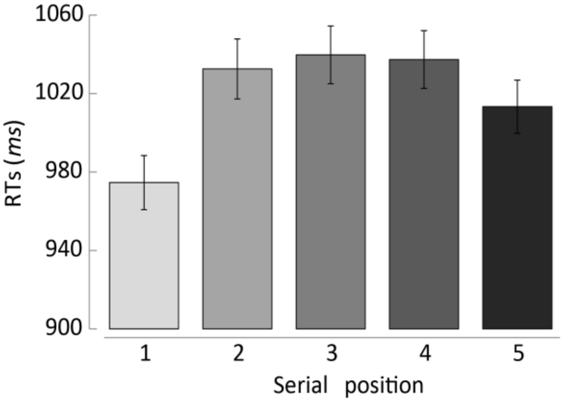

Figure 9.2. Mean reaction times (RTs) results of the recognition phaseError bars indicate standard errors of the mean.

Recognition phase: Absolute Eye Position

Congruent with our hypothesis, a main effect of SP characterized the absolute change in horizontal EP, *F*(4, 1518.13)=6.17, *p*<.002 (see **Figure 9.3a**). Specifically, the middle item was characterized by higher absolute values of horizontal EP than all the other items (all *p*s<.03), except for the second one (*p*=.63). Critically, the first and the last items, were significantly different from the others (all *p*s<.005), except for the fourth, showing again the presence of primacy and recency effects. **Table 9.2** shows the fixed effects comparisons between the five levels of SP. This pattern of results indicates less involvement of overt attentional resources for the first and the last serially-presented items. Finally, analysis on the absolute vertical EP did not show any significant effect of SP, *F*(4, 1518.1)=1.96, *p*=.1 (see **Figure 9.3b**).

Table 9.2. Fixed effects comparisons, with Bonferroni corrections, between the five levels of serial position (SP) for the absolute change in horizontal Eye Position (EP). Means (°) and standard errors, in parentheses, are reported along the diagonal for each SP. Parameter estimates for fixed effects and *t*-test results are reported for all comparisons.

° visual angle	**SP 1**	**SP 2**	**SP 3**	**SP 4**	**SP 5**
SP 1	***M*=.36** *(.02)*	*b*=-.132 *[-.214; -.049]* $t_{1518.02}$=3.13 *p*<.005	*b*=.152 *[.069; .234]* $t_{1518.06}$=3.63 *p*<.001	*b*=.025 *[-.056; .106]* $t_{1518.12}$=.61 *p*=.54	*b*=-.001 *[-.083; .082]* $t_{1518.23}$=-.02 *p*=.99
SP 2		***M*=.49** *(.04)*	*b*=.02 *[-.063; .104]* $t_{1518.09}$=.48 *p*=.63	*b*=-.106 *[-.189; -.024]* $t_{1518.04}$=-2.53 *p*<.02	*b*=-.132 *[.-216; -.048]* $t_{1518.11}$=-3.09 *p*<.005
SP 3			***M*=.52** *(.04)*	*b*=-.127 *[-.209; -.045]* $t_{1518.12}$=-3.03 *p*<.005	*b*=-.153 *[-.236; -.069]* $t_{1518.35}$=-3.58 *p*<.001
SP 4				***M*=.39** *(.03)*	*b*=-.026 *[-.109; .057]* $t_{1518.24}$=-.62 *p* = .54
SP 5					***M*=.35** *(.02)*

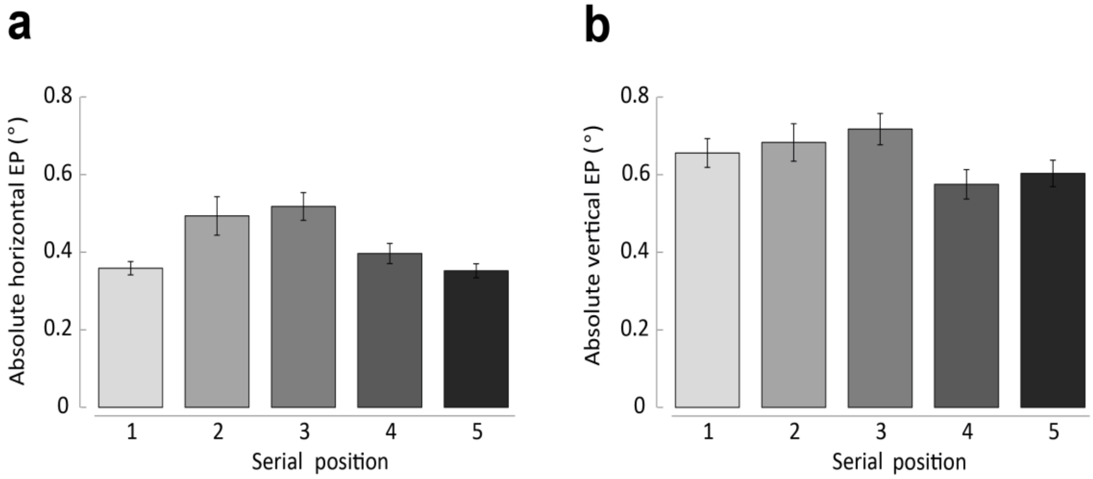

Figure 9.3. Results of the recognition phase. (b) and (c) show the mean change in absolute horizontal and vertical Eye Position (EP). Error bars indicate standard errors of the mean.

Recognition phase: Directional Eye Position

Analysis on the directional values of horizontal EP, *F*(4, 1518.26)=1.26, *p*=.28, and vertical EP, *F*(4, 1518.08)=.55, *p*=.7, did not show any significant effect of SP.

Recall phase

In the recall task, SP was entered in the analysis as a fixed factor[2].

Recall phase: Eye Position

The analysis on horizontal EP revealed a significant effect of SP, *F*(4, 905.99)=8.3, *p*<.001. Since the significant effect indicated the presence of a left-to-right shift of EP, planned polynomial contrasts were used to test for linear and nonlinear effects of SP. Consistent with the hypothesis, the planned polynomial contrast demonstrated a significant linear trend of SP, *t*(905.99)=4.78, *p*<.001, indicating a left-to-right shift of EP with increasing serial position (see **Figure 9.4a**).

Conversely, analysis on the vertical EP did not evidence any consistent effect of SP, included as a fixed factor, *F*(4, 906.03)=.482, *p*=.75 (see **Figure 9.4b**).

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[2] As for the recognition phase, when the digits' numerical magnitude (Small: 1-5; Large: 6-10) was entered in the analyses, neither the main effect nor the interaction with SP were found to be significant.

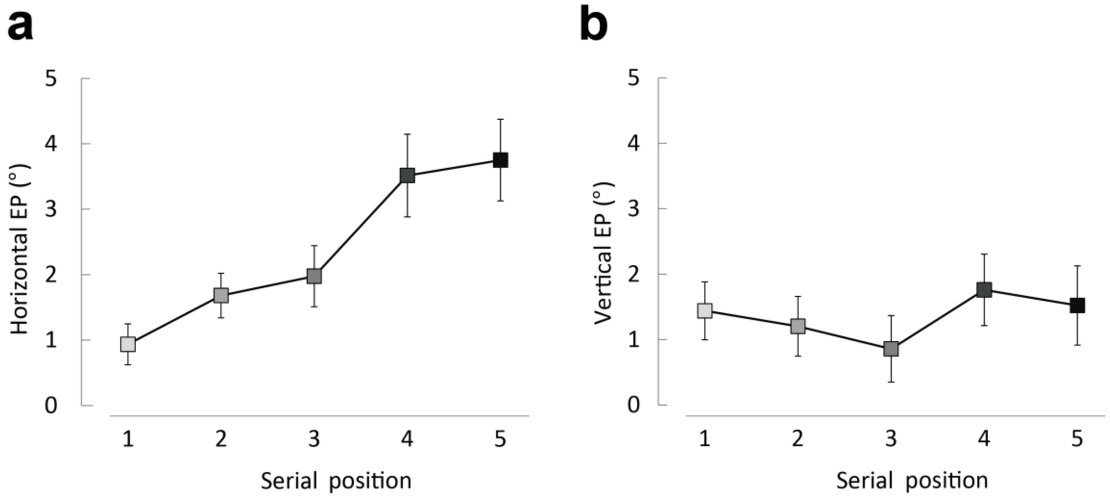

Figure 9.4. Results of the recall phase. (a) shows the horizontal Eye Position mean (°) for the five serial positions. Similarly, (b) shows the vertical Eye Position mean (°) for the five serial positions. Error bars indicate standard errors of the mean.

9.4. DISCUSSION

The present study investigated whether serial order processing exploits overt visuospatial attentional resources, since recent evidence has suggested that serial order would be grounded on the spatial attention system (Abrahamse et al., 2014). Accordingly, we found that overt spatial attention orients the scanning of serially-ordered verbal items. The reported systematic involvement of ocular strategies in a pure verbal task may have far-reaching implications for different areas of cognitive science, since understanding the temporal order of events is fundamental to building memories and, more generally, to learning (Baddeley, 2012; Lashley, 1951).

First, the present findings reveal the role of the oculomotor system in exposing the link between space and serial order in WM: searching for and retrieving ordered information is found to be mirrored by spontaneous horizontal eye movements. In particular, recognizing central items of a memorized ordered sequence required longer inspection times and, critically, a greater involvement of overt attentional resources, than recognizing the first presented item. Conversely, the retrieval of the serially first item was characterized by lower reaction times and by less involvement of overt attentional resources, disclosing primacy effect also in oculomotor-related processes. A similar pattern also characterized the last item. Moreover, the results of the recall task show that serial order is encoded from left-to-right, since eye position deviated the more to the right, the later the serial position in the sequence. While previous findings (van Dijck et al., 2013; 2014) reported a critical role of covert visuospatial attention in mediating space-serial order interactions in a probe recognition-task, these results show that the access to ordered information recruits overt shifts of spatial attention in both recognition and recall. Such spontaneous changes in eye position can be considered as an overt behavioral sign of moving along a spatial representation of ordered information. More widely, these findings support the view of working memory as an interface between internal attention and external attention (Chun, Golomb & Turk-Browne, 2011).

A recent account proposed that the left-to-right orientation of the serial representation would be grounded on consolidated directional routines and, more specifically, on reading habits (Abrahamse et al., 2014). The reading and writing strategies are governed by strict rules that orient the oculomotor system in an ordered direction, through both space and time. Such routines would be, in turn, exploited to scan external space (Rinaldi et al., 2014) and would also strongly bias the directionality of spatiotemporal schemas (Tversky et al., 1991). In the present study, the pattern of results found in the recall phase, with eye positions shifting from left-to-right with increasing serial position, offers support to this view, suggesting a critical influence of directional practices. However, only future studies comparing left-to-right and right-to-left readers, will establish the real impact of these cultural practices. They might also shed light on the potential primacy of a left-to-right attentional orienting in both animals and humans (Brugger, 2015; Rugani, Vallortigara, Priftis & Regolin, 2015; see also de Hevia et al., 2014).

While a clear-cut left-to-right encoding characterized the eye position during recall of the memorized sequence, no similar spatial indexes emerged in the probe-recognition phase. Although apparently in contrast with previous reports (van Dijck & Fias, 2011; van Dijck et al., 2013; 2014), differences between studies may be rather informative. First, in the present study we observed a primacy effect and a non-significant trend for recency (e.g., Burrows & Okada, 1971; Corballis, 1967; Corballis et al., 1972), contrary to a linear increase of reaction time with serial position (e.g., van Dijck & Fias, 2011). While this pattern might have been determined by some experimental details, such as the instruction to recall the exact order of digits (see Corballis, 1967), it can also indicate that participants adopted a self-terminating scan, rather than a full serial scanning strategy (see McElree & Dosher, 1989). Indeed, evidence suggesting that the final element in a sequence might be directly accessible in memory is not missing (Morra, Calvini & Bracco, 2009). This, in turn, can explain the absence of a left-to-right eye shift during the probe recognition phase. Second, in the present study participants were constantly required to maintain fixation before stimulus presentation, in both phases 1 and 2. This requirement might have constrained the degree of freedom of eye movements, minimizing overt scanning. Consistent with this explanation, a forced fixation during retrieval is known to be associated with a reduced episodic memory performance (Johansson & Johansson, 2014; Laeng & Teodorescu, 2002). Future studies, possibly comparing visual to auditory presentation, are needed to better explore this possibility and to disclose further potential differences between covert and overt attentional mechanisms during serial processing.

The issue of serial order representation has a long history in psychology, with different accounts that have been proposed over the years (see for a review, Hurlstone, Hitch & Baddeley, 2014). Although associative chaining was the oldest and most popular approach to serial order, its limits in explaining several findings justified the development of several alternatives (Hurlstone et al., 2014). Among the most recent theories, a very influential model is the Start-End Model (Henson, 1998b), according to which items at the beginning and at the end of the serial sequence possess more distinctive position markers than items in middle of the sequence. Interestingly, one signature of this model is to envisage serial order in analogy with space. Elements of the memorized sequence, indeed, might be conceived as arranged on a horizontal array. Accordingly, in the present study, the facilitation in recognizing first and last elements was accompanied by less involvement of overt attentional resources. Since the first and last elements are associated to the most distinctive markers, these findings uncover the functioning of the mind’s eye during serial processing. Furthermore, the left-to-right shift of eye position during recall provides empirical evidence for a representation of serial order on positional coordinates anchored along the horizontal dimension of space (cf. see also Harcum, 1975).

More generally, the present study highlights the role of visual scanning in verbal memory processing. Indeed, visuospatial strategies can be often adopted to solve pure verbal tasks (Robertson, 1990; Weinberg et al., 1972). In particular, representing visually the memorized ordered sequence might be a helpful strategy to store and manipulate the ordered information. Accordingly, a critical role of visual-imagery strategies in verbal memory processing has been suggested (Gerton, Brown, Meyer-Lindenberg, Kohn, Holt, Olsen & Berman, 2004). Various studies, indeed, reported that mental imagery is often accompanied by eye movements (e.g., Spivey & Geng, 2001). Rather than just mirroring the internal scanning, the recruitment of oculomotor strategies during mental imagery is conceived as functional and even essential to memory retrieval (Hebb, 1968; Laeng & Teodorescu, 2002). For instance, insight is improved when attention is shifted through space congruently to a problem’s solution (Thomas & Lleras, 2007; 2009). The present findings support these suggestions by showing that verbal memory tasks are approached through systematic overt visuospatial strategies. In particular, participants might have adopted spatial schemas to represent the serial sequence, with eye movements that were used to connect elements of the internal representation with respect to the external world. Thus, coordinates of the internal space might have been fixed to external coordinates to provide the ground for the serial representation.

Of clinical relevance, by demonstrating the role of the oculomotor system in mediating space-time interactions, the present results provide insights into eye-movement-based therapies hitherto used in psychiatry, even though controversially discussed (Davidson & Parker, 2001; Herbert, Lilienfeld, Lohr, Montgomery, O'Donohue, Rosen & Tolin, 2000). In particular, in these therapies horizontal eye movements would favour the recall of memories by taxing WM, a system partially responsible for vividness and emotionality of aversive memories (Andrade, Kavanagh & Baddeley, 1997; Baddeley & Andrade, 2000; Gunter & Bodner, 2008; Lee & Cuijpers, 2013; Shapiro, 1989). In the present study, memory processing was found to be mediated by eye movements, with greater involvement of oculomotor resources in recalling the centrally-positioned, “hidden” (Henson, 1998b), elements. Thus, eye movements *per se* may act as a helpful tool for an active search in memory (see Johansson & Johansson, 2014). In particular, the overt visuospatial attention mechanisms reported here may well hold for extracting both newly learned and overlearned temporal information, as autobiographical memories (see Hartmann, Martarelli, Mast & Stocker, 2014). Although so far speculative, facilitation of eye movements during serial order and temporal processing might be substantiated by future research.

In conclusion, we showed that eye movements mediate the search and the retrieval of ordered verbal information, disclosing that space-time association relies on spatial attention (see **Chapter 1)**. Working memory has been recognized as the workspace where relational representations are assembled together (Halford, Wilson & Phillips, 2010). The present study brings further support to this view and, more generally, to the idea that visuospatial attention orients the mind’s eye through spatiotemporal representations. Whether the retrieval of emotional memories similarly involves automatic oculomotor behavior is a challenging question with considerable importance for clinical psychiatry.

WALKING ON A MENTAL TIME LINE:

Temporal processing affects step movements along the sagittal space

Chapter adapted from:
Rinaldi, L., Locati, F., Bernardi, N.F., Parolin, L., & Girelli, L. (*under review*). Walking on a mental time line: Temporal processing affects step movements along the sagittal space.

10.1. INTRODUCTION

'Sally, take my hand
We'll travel south crossland
Put out the fire
Don't look past my shoulder.'

- Pete Townshend (1971)

Space and time are strictly coupled to each other in both the physical world and in the human mind (see **Chapter 1**). For instance, we subjectively experience that the passage of time goes along with the passage of space when we move from one place to another. Accordingly, a large body of evidence indicates that time can be represented along an horizontal continuum, as flowing from one extremity to another (i.e., left or right) depending on reading habits (see **Chapter 8** and **Chapter 9**). Similarly, compelling evidence indicates that time can be represented along a sagittal continuum (see for a review Bender & Beller, 2014; see **Chapter 1**). In particular, two main hypotheses have been so far proposed to account for the metaphor of time along the sagittal space as a "river in movement": the Moving Time perspective and the Moving Ego perspective, respectively (e.g., Clark, 1973). From the Moving Time perspective, we regard ourselves as stationary and time as moving towards us, like for instance when we say "We are approaching Sunday" (Clark, 1973). From the complementary and more prevalent Moving Ego perspective, we regard ourselves as moving downstream through a stationary time. Hence, according to this perspective, we would approach future events and leave them behind in both space and time (Clark, 1973). In line with this, manual responses to past- and future-related words are faster when the response direction is compatible with a back-to-front mental time line (MTL) (Ulrich et al., 2012; Sell & Kaschak, 2011; see also Torralbo et al., 2006). Furthermore, postural sway during mental time travel is congruent with the direction of mental metaphors, i.e., Western individuals move slightly backward when thinking about their past and move forward when thinking about their future (Miles, Nind & Macrae, 2010).

Insofar, these findings are consistent with the proposal of the Moving Ego metaphor of time, though direct evidence supporting this representation is still needed (Bender & Beller, 2014). In fact, the egocentric MTL is supposed to originate from our walking experience in the physical world: as people typically walk in forward direction, they consequently move forward through both space and time (Clark, 1973). Nevertheless, previous studies have explored the influence of temporal processing only on the execution of manual responses that were furthermore restricted to the frontal space (Ulrich et al., 2012; Sell & Kaschak, 2011). Thus, these studies do not allow to fully support the existence of an egocentric MTL, where the past and the future are conceived as behind and as in front of the body, respectively. On these grounds, here we reasoned that if the egocentric MTL originates from walking, temporal processing should affect step movements along the sagittal space.

Participants were asked to categorize auditory words referring either to the past (e.g., *yesterday*) or to the future (e.g., *tomorrow*) by means of whole-body single-step movements. In particular, as soon as the auditory word was presented, they had to make a step with their right leg in the backward direction (step backward) or in the forward direction (step forward), whereas they had to keep the left foot in the starting position. Critically, participants took part in two experimental blocks, one in which they had to make a step back in response to past-related words and a step forward in response to future-related words (congruent condition), and one with the reversed assignment (incongruent condition). Kinematic parameters were acquired through an optoelectronic system, allowing us to explore both initiation time and total duration of the step movements, as well as the width covered by each step.

According to the Moving Ego perspective of time, we predict that participants should initiate step backwards much faster in response to past-related words, whereas they should initiate much faster step forward in response to future related words. This facilitation should be observed in the step initiation time, but not in the total duration and in the step width. In fact, in line with previous evidence (Ulrich et al., 2012), we expect that the spatial schema of the MTL should operate primarily on cognitive processes that involve the initiation of the motor response, rather than on late motor processes.

10.2. METHODS

Participants

Nineteen Italian right-handed participants (17 females; *M* age=29.7 ys, *SD*=2.9) were involved in this study. Handedness was assessed by means of the Edinburgh Inventory (Oldfield, 1971) and participants were also asked to indicate their dominant foot (e.g., “*Which foot do you usually kick with*?”). All participants were classified as right-handed as well as right-footed. All participants expressed written informed consent to participate in the study. The study protocol was approved by the ethics board of the University of Milano-Bicocca.

Apparatus, procedure and stimuli

Participants were blindfolded throughout the experiment in order to avoid any visual feedback and were instructed to stand still at the beginning of each trial (starting position). Participants were asked to categorize auditory words referring either to the past or to the future, by means of whole-body single-step movements with their right leg. To help participant staying stationary with their left leg during the task, a small parallelepiped-like object (height: 1 cm) was fixed to the ground in the starting position. This object served as a passive haptic feedback of the starting position point (see **Figure 10.1**).

Each trial began with the presentation of the auditory word. As soon as the auditory word was presented, participants had to make a fluent step only with their right leg in the backward direction (step backward) or in the forward direction (step forward), whereas they had to keep the left foot in the starting position. After movement completion, participants had to step back to the starting position, waiting for the next trial (time interval between trials: 3000 ms). Each participant took part in two experimental blocks, one in which they had to make a step back in response to past-related words and a step forward in response to future-related words (congruent condition), and one with the reversed assignment (incongruent condition). The order of blocks was counterbalanced across participants.

In each block, 46 auditory Italian words were used (12 adverbs and 34 verbs), half of them referring to past and half of them to future (see **Table 10.1**; see for a similar method, Torralbo Santiago & Lupiáñez, 2006). Stimuli lasted 800 ms, had equal auditory properties (44,100 Hz, 32 bits, stereo) and were played at a constant intensity level through loudspeakers (Logitech Speaker System Z520), placed near the left-sided participant’s coronal plane. The different words were presented in a pseudo-random order using E-prime2 (Psychology Software Tools, Pittsburgh, PA).

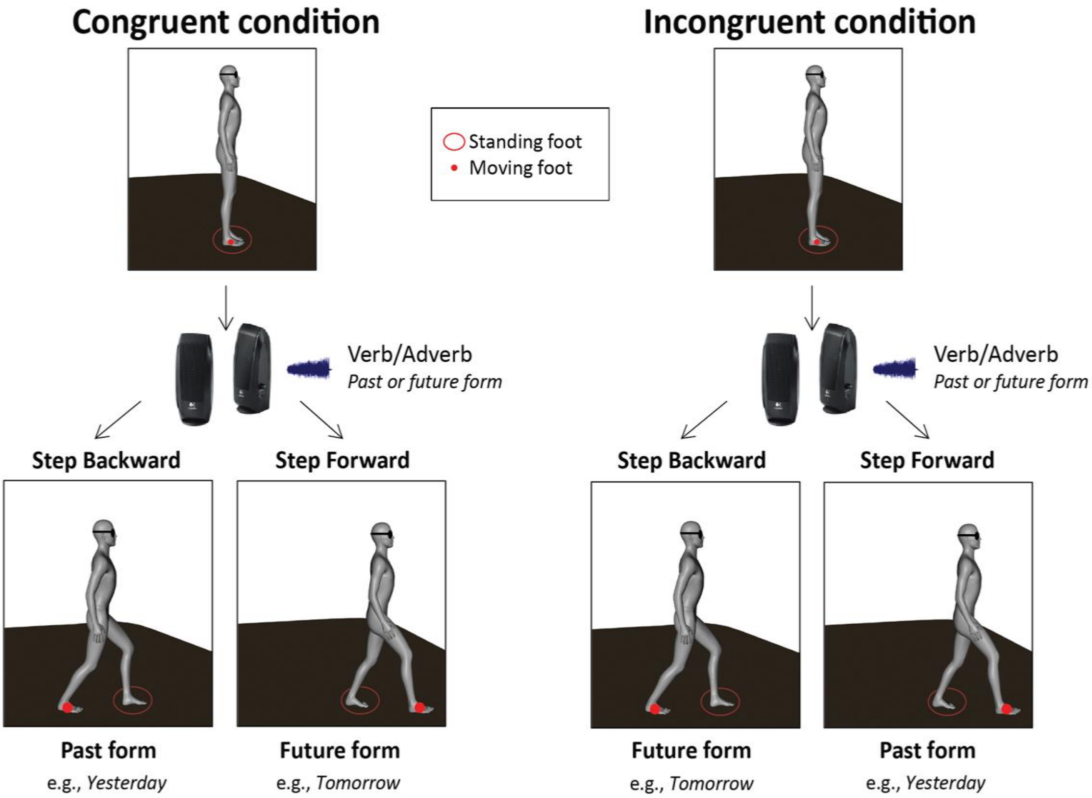

Figure 10.1. Apparatus and procedure of the study. Participants were asked to categorize acoustic words referring either to the past or to the future, by means of whole-body single-step movements. A 3D-optoelectronic motion analyzer recorded the 3D spatial position of passive reflective markers fixed on the body's surface. In the congruent condition, participants had to make a step back/forward in response to past/future-related words and *vice versa* for the incongruent condition.

Table 10.1. Verbs and adverbs in the past- and future-related forms that were used in this study. In each block (congruent and incongruent conditions) 46 auditory Italian words were used (12 adverbs and 34 verbs). Half of the words referred to the past and half to the future. Italian words are followed by the English translation in parenthesis.

Past	**Future**
Ieri (Yesterday)	*Domani* (Tomorrow)
Prima (Before)	*Dopo* (After)
Precedentemente (Earlier)	*Prossimamente* (Soon)
Recentemente (Recently)	*Presto* (In a while)
Precedente (Previous)	*Prossimo* (Next)
Scorso (Last)	*Imminente* (Imminent)
Disse (He said)	*Dirà* (He will say)
Fece (He did)	*Fara* (He will do)
Mangiò (He ate)	*Mangerò* (He will eat)
Guardò (He saw)	*Guarderà* (He will see)
Scrisse (He wrote)	*Scriverà* (He will write)
Pianse (He cried)	*Piangerà* (He will cry)
Sorrisero (They smiled)	*Sorrideranno* (They will smile)
Lavorarono (They worked)	*Lavoreranno* (They will work)
Vollero (They wanted)	*Vorranno* (They will want)
Decisero (They decided)	*Decideranno* (They will decide)
Chiesero (They asked)	*Chiederanno* (They will ask)
Pensammo (We thought)	*Penseremo* (We will think)
Mostrammo (We showed)	*Mostreremo* (We will show)
Andammo (We went)	*Andremo* (We will go)
Bevemmo (We drank)	*Berremo* (We will drink)
Soffrimmo (We suffered)	*Soffriremo* (We will suffer)
Comprammo (We bought)	*Compreremo* (We will buy)

Data acquisition and analysis

A 3D-optoelectronic motion analyzer (SMART system, sampling rate of 120 Hz, spatial resolution ≈ 0.3 mm) recorded the 3D spatial position of four passive reflective marker fixed on the participant’s right (Marker 1) and left (Marker 2) foot (i.e., on the base of the fifth metatarsal) and on the participant's right (Marker 3) and left (Marker 4) knee (i.e., on the lateral femoral epicondyle). Marker 1 was used to compute the reaction times (RTs), defined as the time elapsed between the onset of the auditory word and the onset of the step movement. The beginning of the step was measured as the first frame during which the displacement of the foot marker along any Cartesian body axis increased more than 0.3 mm, with respect to the previous frame (RTs were also analogously computed for Marker 3). The detection of movement onset was performed automatically via software and for each movement was visually checked and manually corrected when necessary. Marker 1 was used also to compute the total step time (STotDur), defined as the time elapsed between step onset and offset. Furthermore, the same marker was used to compute the maximum step width (MSW), defined as the maximum distance between step onset and offset along any Cartesian body axis. Data were analyzed offline for each trial and then averaged across trials for each experimental condition and participant, with a custom software written in MATLAB version 7.7 (R2008b). A repeated measures analysis of variance (ANOVA) with step direction (backward, forward) and temporal reference (past, future) as within subjects variables was performed on RTs, STotDur and MSA. The presence of a congruency effect between step direction and temporal reference was tested by the interaction in the ANOVA.

10.3. RESULTS

The overall mean RTs was 1263 ms (91.3% of the total trials). Analysis revealed that the main effects of step direction, *F*(1, 18)=3.36, *p*=.08, and of temporal reference, *F*(1, 18)=1.12, *p*=.31, were both not significant. Critically, a significant interaction between step direction and temporal reference was found, *F*(1, 18)=56.09, *p*<.001, η^2_p=.76. Post-hoc comparisons showed that steps backwards were initiated faster in response to past- (*M*=1168 ms, *SD*=201) than to future-related words (*M*=1397 ms, *SD*=257; *p*<.001), whereas steps forward were initiated faster in response to future- (*M*=1152 ms, *SD*=204) than to past-related words (*M*=1335 ms, *SD*=235; *p*<.001), thus indicating the presence of a congruency effect (**Figure 10.2**). Individual congruency effects for steps backward and forward (individual mean of the incongruent conditions subtracted from the individual mean of the congruent condition) are reported in **Figure 10.3**.

Additional analyses on RTs of Marker 3 (i.e., lateral epicondyles of the right knee) led to similar results. The overall mean RTs for Marker 3 was 1097 ms. Analysis revealed a main effect of step direction, *F*(1, 18)=10.31, *p*<.05, η^2_p=.36, with faster RTs for forward (*M*=1064 ms, *SD*=229) than backward steps (*M*=1113 ms, *SD*=254), that reflects the anatomic and functional asymmetry favoring forward rather than backward walking (Grasso, Bianchi & Lacquaniti, 1998; Thorstensson, 1986). The main effect of temporal reference was not significant, *F*(1, 18)=2.23, *p*=.15. Critically, a significant interaction between step direction and temporal reference was found, *F*(1, 18)=45.53, *p*<.001, η^2_p=.71. Post-hoc comparisons showed that steps backwards were initiated faster in response to past- (*M*=1011 ms, *SD*=213) than to future-related words (*M*=1249 ms, *SD*=238; *p*<.001), whereas steps forward were initiated faster in response to future- (*M*=978 ms, *SD*=193) than to past-related words (*M*=1149 ms, *SD*=236; *p*<.001), thus indicating the presence of a congruency effect also for RTs of Marker 3.

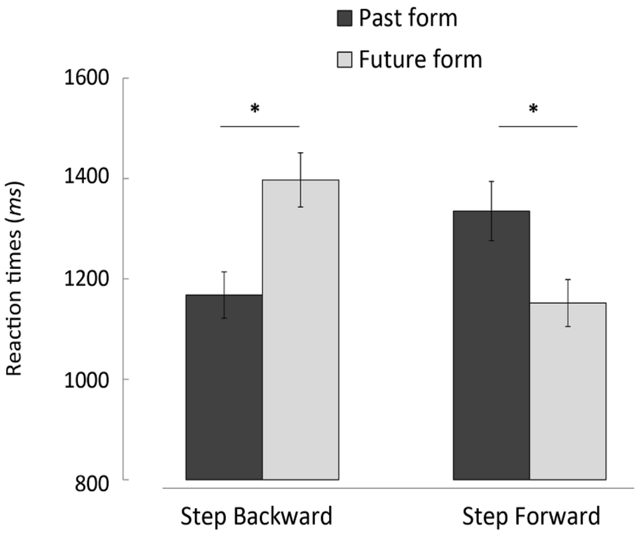

Figure 10.2. Movements RTs. Steps backward were initiated faster in response to past- than to future-related words, whereas steps forward were initiated faster in response to future- than to past-related words.

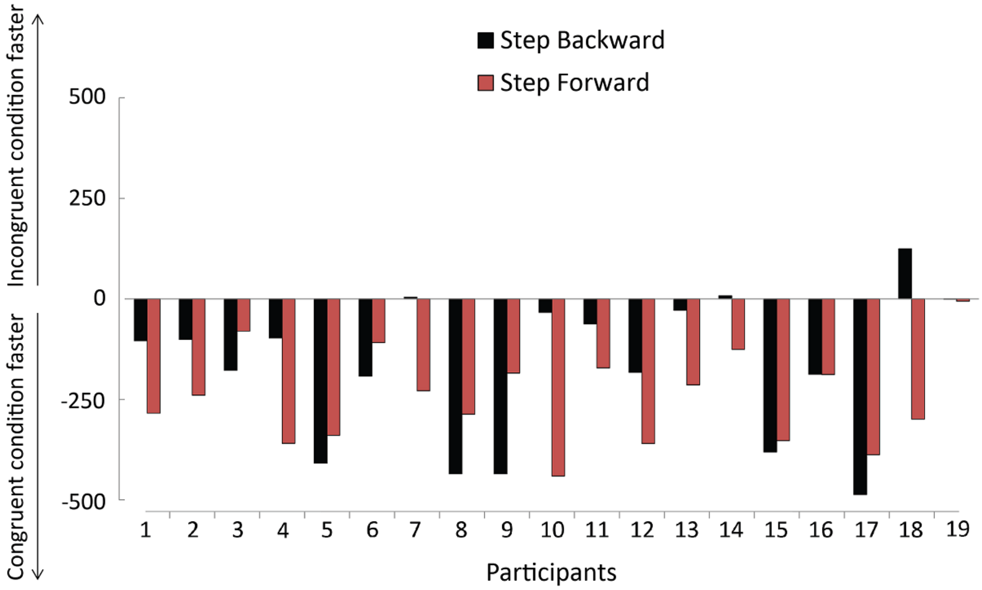

Figure 10.3. Individual congruency effects for steps backward and forward (individual mean of the incongruent conditions subtracted from the individual mean of the congruent condition). Negative values indicate that steps were initiated faster in the congruent condition.

The overall mean STotDur was 665 ms. Analysis revealed only a main effect of step direction, *F*(1, 18)=45.14, *p*<.001, η^2_p=.72, with shorter duration for forward (*M*=617 ms, *SD*=92) than backward movements (*M*=712 ms, *SD*=96), that reflects the biomechanical advantage in making forward steps (Grasso, Bianchi & Lacquaniti, 1998; Thorstensson, 1986). On the contrary, both temporal reference, *F*(1, 18)=3.33, *p*=.09, and the interaction between step direction and temporal reference, *F*(1, 18)<1, *p*=.51, were not significant (**Figure 10.4**).

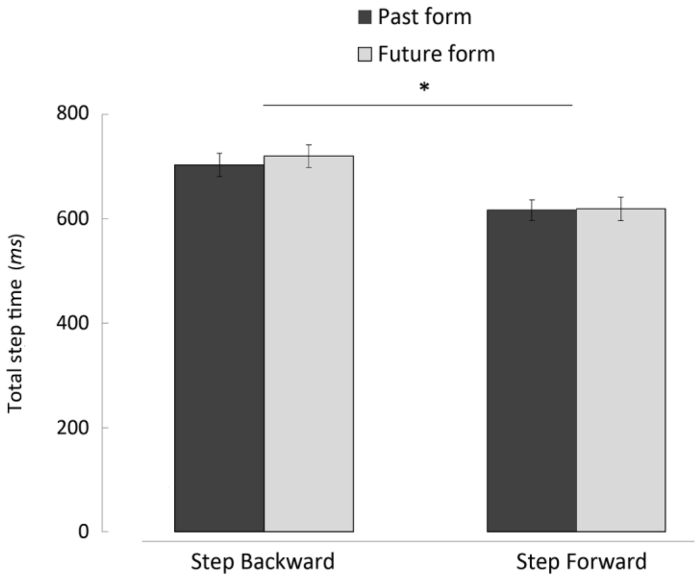

Figure 10.4. Mean duration of backward and forward steps. The total step time (STotDur) was shorter for steps forward than steps backward, but was not influenced by temporal reference of the auditory words.

Finally, the overall mean MSW was 363 mm. Results did not show any significant effect of step direction, *F*(1, 18)<1, *p*=.76, of temporal reference, *F*(1, 18)< 1, *p*=.73, and of the interaction, *F*(1, 18)<1.05, *p*=.32 (**Figure 10.5**).

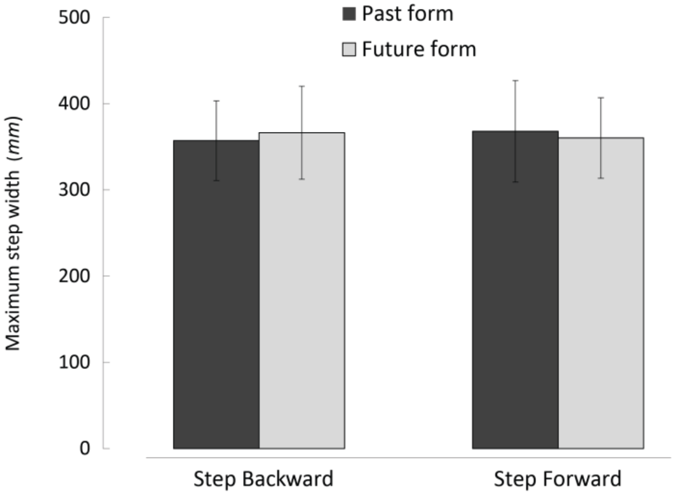

Figure 10.5. Mean maximum width of backward and forward steps. The maximum step width was not affected by neither step direction nor by temporal reference.

10.4. DISCUSSION

The present study probed the embodied hypothesis underlying the Moving Ego perspective of time (Clark, 1973; see **Chapter 1**). This was done by asking participants to categorize auditory words referring either to the past or to the future with single-step movements directed either in the back or in the front space. Kinematic results showed that participants initiated steps backward much faster in response to past- than to future-related words, whereas they initiated steps forward much faster in response to future- than past-related words. This work provides, therefore, the first demonstration that temporal processing affects the motor programming of whole-body movements. Furthermore, since the reported compatibility effect was limited to movement initiation time, it is likely that the processing of temporal information acted on the early stages of response selection (see Ulrich et al., 2012).

Beyond substantiating the long-standing hypothesis that humans spatialize time on an egocentric spatial frame of reference, our findings demonstrate that the intangible domain of time extends to the more concrete domain of space through our body's action in the physical world. The tight coupling between temporal and spatial processing, indeed, has been previously suggested to support an embodied view of cognition (Kranjec & Chatterjee, 2010). Embodied cognition theories maintain that abstract cognitive processes make use of sensorimotor processes and suggest that abstract concepts are shaped by constraints and experiential couplings imposed by human physiology, as reflected in perception and action (Wilson, 2002). In this sense, we may think and talk about past as being "behind us" because, when we walk, what has been already experienced in time tends also to be located in the space behind us. Hence, spatial relations from the more concrete domain of space would provide structure for the more abstract domain of time. Our results offer novel evidence supporting the embodied cognition of temporal concept (Kranjec & Chatterjee, 2010). More generally, these findings indicate that spatial and temporal relations share many similarities, being associated to each other in our experience.

Critically, recent evidence has shown that temporal order processing engage the visual cortex and the precuneus, as well as the IPS, all brain areas that are part of the neural network linked to visuospatial imagery and visuospatial attention (D'Argembeau et al., 2015; see also Rinaldi, Brugger et al., 2015). This study adds to the existing evidence by indicating that the embodied sagittal MTL engages also sensorimotor representations (Miles et al., 2010). Future studies investigating the neural basis of temporal order processing will clarify the extent to which the embodied MTL relies on the motor system.

A previous study explored the role of passive whole-body motion along the sagittal space on the processing of temporal information (Hartmann & Fast, 2012). In this study, the effect of whole-body motion was, however, limited to the processing of future-related verbal information. To account for this finding, Hartmann and Fast (2012) suggested that the sensorimotor system might be more closely related to the representation of future events than to the representation of past events, because in everyday life people move more often forward than backward. Nevertheless, passive whole-body engages less sensorimotor resources than active locomotion, thus inducing a limited activation of the MTL. Indeed, the sagittal MTL is supposed to originate from an active motion of the ego through space and time. Accordingly, the present study showed that when participants actively move along the sagittal space, a compatibility effect is found for both past- and future-related words.

In summary, we report here the first kinematic evidence in support of the Moving Ego metaphor of time (Clark, 1973), according to which we would approach future events and leave them behind, as moving through a MTL projected on a physical space. Whether cultural attitudes toward time might influence the motor link between space and time is a challenging question for a comprehensive understanding of our representation of temporal concepts (de la Fuente, Santiago, Román, Dumitrache & Casasanto, 2014).

CHAPTER 11

DISTANCING THE PRESENT SELF FROM THE PAST AND FUTURE:

Psychological distance in anxiety and depression

Chapter adapted from:
Rinaldi, L., Locati, F., Parolin, L., & Girelli, L. (*under review*). Distancing the present self from the past and the future: Psychological distance in anxiety and depression.

11.1. INTRODUCTION

Humans have a unique ability to think, experience and orients toward time (Suddendorf & Corballis, 2007). In everyday life, people frequently relive past events and entertain possible future scenarios, engaging in what has been referred as “mental time travel” (Suddendorf & Corballis, 1997). Critically, this mental time travel is a significant human attribute that allows us to build up a sense of coherence and a narrative structure of the self (Crossley, 2000; Polkinghorne, 1991). Along this view, Husserl (1991) conceptualized that we cannot experience anything as happening, except against the background of what it succeeds and what we anticipate it will succeed. An implicit sense of connection, order and experiential unity in everyday life between the past and the future is, indeed, paramount to preserve a coherent personal identity and to understand relationships between the self and the others (Crossley, 2000). Accordingly, when such connection is disrupted, the individual has to deal with the need to reconstruct a sense of order (Crossley, 2000).

But how do people perceive the psychological distance from their own past and future events? Psychological distance is the subjective feeling of distance in time, in space and in social interaction (Trope & Liberman, 2010). A recent study indicated that individuals do not perceive the psychological distance of past and future events as equidistant from the present (Caruso et al., 2013). In particular, Caruso and colleagues (2013) hypothesized that the spatial metaphor of events in time, according to which people move from the past toward the future on a time projected onto physical space (see for a review Bender & Beller, 2014; see **Chapter 10**), influences the psychological distance of future and past events. In fact, direct experiences with concrete spatial distances would shape the more abstract domain of time and, specifically, the psychological distance of time (Trope & Liberman, 2010). Because “approaching the future” along an egocentric mental time line implies perceiving events as closer, and *vice versa* when “leaving behind the past” (see also Kruglanski, Pierro & Higgins, 2015), Caruso et al. (2013) suggested that diminishing temporal separation would make events also temporally closer, and increasing temporal separation would make them temporally more distant. Results from different experiments supported this hypothesis, indicating a systematic tendency to experience the future as psychologically closer than the past (Caruso et al., 2013). This temporal asymmetry suggests, therefore, that patterns of perceived movement through space are associated with similar patterns of perceived movement through time, and may indicate that people reduce the psychological distance from the present to prepare for the upcoming future.

Interestingly, this future-oriented thinking may be extremely functional in humans, because future events can be acted on, whereas past events cannot (Horwich, 1987). In fact, representing the future as close may prepare people to approach or avoid a certain event in a more concrete way (Trope & Liberman, 2010). In line with this, people tend to make more emotional investment toward future than past events (D'Argembeau & van der Linden, 2004; Van Boven & Ashworth, 2007) and to judge transgressions more harshly if they would take place in the future than in the past (Caruso, 2010). Furthermore, reducing the psychological distance between the present self and temporal events increases significantly people's emotional arousal (Caruso et al., 2013; Kross & Ayduk, 2011).

Nevertheless, though psychological distance of temporal events has been shown to shape emotions, little is still known about the other way round. A single recent study investigated the effect of negative emotions, and specifically of rumination, on temporal asymmetries (Siedlecka, Capper & Denson, 2015). Results showed that the more people dwell on negative event, a central feature of ruminative thinking, the more they perceive this event as psychologically closer (Siedlecka et al., 2015). Insofar, this finding indicates that negative emotions, such as anger, guilt, and sadness, can all induce a sense of closeness with respect to future scenarios (see also Van Boven, Kane, McGraw & Dale, 2010).

Interestingly, clinical literature has for long suggested that depression anchors the self to the past, whereas anxiety to the future (Kendall & Watson, 1989). In fact, scattered evidence has so far shown that that anxiety disorders are associated more to future threat life events, whereas depression to loss events (e.g., Finlay-Jones & Brown, 1981; Sandin, Chorot, Santed & Valiente, 2004; Surtees, 1995). Yet, no study has so far systematically explored such relationship. Only one study tried to link anxious and depressive events with temporal thinking (Eysenck, Payne & Santos, 2006). In particular, Eysenck et al. (2006) found that anxious experiences tend to be associated to negative events in the future, whereas depressive experiences to negative events in the past.

On these grounds, here we attempt to provide the first empirical evidence that people with depression- and anxiety-related personality traits perceive differently the psychological distance of past and future events. Participants were first asked to think ahead to 1 month from today (future event) or to think back to 1 month ago today (past event), and to score this target day psychological distance as close or far from now (see Caruso et al., 2013). The same participants were then administered the Minnesota Multiphasic Personality Inventory-2 Restructured Form (MMPI-2-RF; Ben-Porath & Tellegen, 2008). This allowed us to identify anxiety-related and depression-related personality traits individuals and to compare them, along with a control group, in terms of psychological distance. According to the clinical distinction (Kendall & Watson, 1989), we first expect individuals with anxiety-related personality traits to show an exaggerated tendency to perceive the future as psychologically closer than the past. Second, we expect this tendency to be drastically reduced in individuals with depression-related personality traits.

11.2. METHODS

Participants

Potential participants were 261 students (52 males; average age 23.8±4.2 years), from the University of Milano-Bicocca. Participants with invalid MMPI-2-RF protocols [Cannot Say (raw score) >18, Variable Response Inconsistency-Revised or True Response Inconsistency-Revised T ≥80, Infrequent Responses-Revised T ≥120, Infrequent Psychopathology Responses-Revised T ≥100] were excluded from the study. These criteria, established in the MMPI-2-RF manual (Ben-Porath & Tellegen, 2008), indicate scale elevations that invalidate the substantive profile. The final sample consisted of 221 individuals (39 males; average age 23.5± 3.6 years).

Measures

Psychological distance

Psychological distance was assessed by asking participants to think ahead to 1 month from today (future event) and to think back to 1 month ago today (past event). Participants were then required to score on a paper the target day psychological distance, from 1 (“really close to now”) to 10 (“really far from now”). The order of events (past and future) was counterbalanced across participants.

MMPI-2-RF

The MMPI-2-RF (Ben-Porath & Tellegen, 2008) contains 338 items and is designed to provide an efficient, comprehensive assessment of the constructs assessable with the MMPI-2 item pool. The MMPI-2-RF consists of 9 validity scales and 42 substantive scales, including the nine previously developed RC Scales (Tellegen et al., 2003) and 33 new scales. The 33 new substantive scales include three Higher Order (H-O) Scales, 23 Specific Problems Scales, two Interest Scales, and a revised version of the Personality Psychopathology Five-Revised (PSY-5; Harkness & McNulty, 1994; Harkness, McNulty & BenPorath, 1995). Extensive psychometric characteristics and external correlates can be found for the scales analyzed in this study in the technical manual for the test (Tellegen & Ben-Porath, 2008). MMPI-2-RF scores were obtained from the full MMPI-2 administration (Tellegen & Ben-Porath, 2008).

Procedure

Participants first completed the psychological distance test and then completed the MMPI-2 according to standard protocol. All participants completed paperwork, prior to the evaluation, granting consent to have test data used for research purposes with all identifying information kept private.

Data analysis and group sampling

The individual psychological distance score was computed by subtracting the scored distance of future event from the scored distance of past event.

Participants were then included in the Anxiety-related personality traits group if the T scores on both the Anxiety (AXY) and the Dysfunctional Negative Emotions (RC7) scales were ≥65, and if the T scores on both the Low Positive Emotions (RC2) and the Introversion/Low Positive Emotionality (INTR-r) scales were <65. On the contrary, participants were included in the Depression-related personality traits group if the T scores on both the RC2 and the INTR-r scales were ≥65, and if the T scores on both the AXY and RC7 scales were <65. Finally, the control groups was composed by participants with T scores <65 in the AXY, RC7, RC2 and INTR-r scales.

The final sample was therefore composed of 133 participants (*M* age=23.35 ys, *SD*=3.25; 24 males), divided in three groups matched for age: an anxiety-related personality traits group (*N*=34), a depression-related personality traits group (*N*=43), and a control group (*N*=56).

11.3. RESULTS

We first performed a series of one-sample *t*-tests on the psychological distance score against zero (i.e., past and future event perceived as equidistant from the present). Results showed that the control group perceived the future as psychologically closer than the past, *t*(55)=4.34, *p*<.001 (*M*=1.36, *SD*=2.33). Critically, this tendency was intensified in the anxiety-related personality traits group, *t*(33)=10.19, *p*<.001 (*M*=2.71, *SD*=1.54), whereas it was absent in the depressed-related personality traits group, *t*(42)=.61, p=.55 (*M*=.23, *SD*=2.51).

We then computed a one-way analysis of variance (ANOVA) with group as between-subjects variable. Results showed that psychological distance differed between the three groups, *F*(3)=11.73, *p*<.001, η^2_p=.16 (**Figure 11.1**). In particular, the tendency to perceive future events as closer was exaggerated in the anxiety-related personality traits group compared to the control group (*p*<.001). On the contrary, this tendency was drastically reduced in the depression-related personality traits group compared to the control group (*p*<.05).

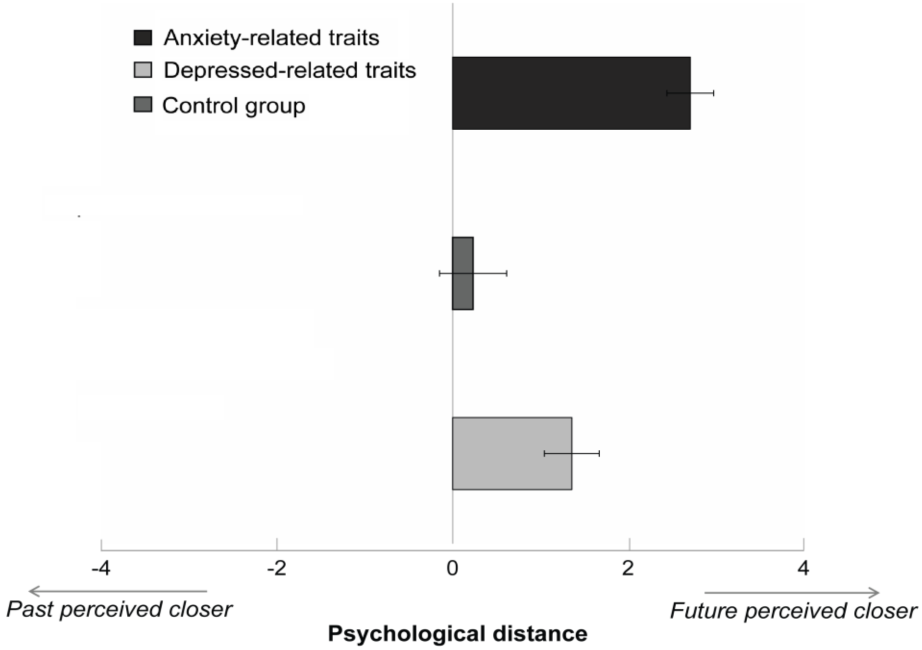

Figure 11.1. Psychological distance in anxiety and depression.
Psychological distance was computed by subtracting the distance reported for future event from the distance of past event. The control group perceived the future as psychologically closer than the past, with this tendency that was intensified in the anxiety-related personality traits group. On the contrary, there was no temporal asymmetry in the depressed-related personality traits group.

11.4. DISCUSSION

The present study investigated the effect of anxiety and depression on the psychological distance of temporal events. Indeed, a recent study by Caruso et al. (2013)

reported a systematic tendency to experience the future as psychologically closer than the past. Since anxiety and depression have been shown to differently associate with past and future events (Eysenck et al., 2006), here we asked whether such relationship may also distort the psychological distance of temporal events. Following previous clinical literature (e.g., Finlay-Jones & Brown, 1981; Kendall & Watson, 1989; Sandin et al., 2004; Surtees, 1995), we hypothesized that individuals with anxiety-related personality traits should show an exaggerated tendency to perceive the future as psychologically closer than the past, whereas this tendency should drastically shrink in individuals with depression-related personality traits. Results of the present study confirmed the above hypotheses, by showing that personality traits linked to anxiety and depression distort the typical orientation toward time. This study provides therefore the first empirical evidence substantiating the clinical hypothesis that the past and the future are differently faced by people with depression- and anxiety-related personality traits.

By asking participants to recall negative past events and to imagine negative future ones, a previous study reported an association between anxiety and negative future events and between depression and negative past events (e.g., Eysenck et al., 2006). The present findings go beyond this preliminary suggestion, by showing that anxiety and depression are not simply associated with past and future, but rather they produce a misperception of psychological distance. Indeed, our participants were not asked to imagine themselves in a negative or positive scenario, as in the study by Eysenck and colleagues (2006). Hence, this altered psychological distance, suggestive of a general predisposition toward time, may reflect a crucial feature that characterizes individuals with anxiety-related and depression-related personality traits.

The systematic tendency to perceive the future as psychologically closer than the past has been suggested to be a consequence of experiential movement through time (Caruso et al., 2013). In particular, this temporal asymmetry would be influenced by the physical egocentric motion toward space, experienced primarily in everyday walking behaviour (see **Chapter 10**). For instance, people perceive objects as closer when they physically approach those objects in space (Lewin, 1935). Since space and time are tightly linked in both the physical world and in the human mind (see for a review, Bender & Beller, 2014), patterns of perceived movement through space would be similar to patterns of perceived movement through time, giving arise to the reported temporal asymmetry. However, while such an embodied interpretation nicely conciliates with findings in the general population, how would it also account for the altered temporal asymmetry in anxiety and depression? Interestingly, motor behavior and motor signs are key criteria of contemporary diagnostic classification systems (DSM-V, ICD-10) for diagnosis of mood disorders, as they also seem to be optimal predictors of the disease (Sobin & Sackeim, 1997). Critically, in depressed patients symptoms often cover alterations of gross motor activity, with a consistent reduction of gait velocity (Michalak, Troje, Fischer, Vollmar, Heidenreich & Schulte, 2009; see for a review Schrijvers, Hulstijn & Sabbe, 2008). Whereas healthy individuals propel themselves forward during walking, depressed patients show a typical lifting motion of the leg that significantly slows down gait velocity (Sloman, Berridge, Homatidis, Hunter & Duck, 1982). Such a difference is not manifested in the time required for stepping, but rather in the spatial distance covered (Lemke, Wendorff, Mieth, Buhl & Linnemann, 2000; Sloman et al., 1982). In fact, a stride hypometria, i.e., shorter step distance, has been reported in depressed patients (Lemke et al., 2000; Sloman et al., 1982). We suggest that the reduced tendency to perceive the future as closer than the past in people with depression-related personality traits might therefore originate from their slowed experiential movement through space and time. In line with this, changes in gait pattern affect the way healthy individuals process negative and positive material (Michalak, Rohde & Troje, 2015). Yet, future research is needed to explore this speculative, though fascinating, link between psychological distance and walking speed in depression.

Whereas an altered gait has been largely documented in depression, no study has so far explored the relationship between anxiety and walking speed. Nevertheless, a possible contribution to the understanding of the present findings may come from studies focused on biological motion perception, i.e., the ability of the human visual system to derive information from the movement of other living things (Johansson, 1973). Indeed, naive observers tend to judge two equally plausible precepts with different facing orientations more often as facing towards them than facing away, a phenomenon named as the “facing-the-viewer bias” (Brooks et al., 2008; Vanrie, Dekeyser & Verfaillie, 2004). Importantly, Heenan and Troje (2015) recently found an association between anxiety and biological motion perception. In particular, greater anxiety was associated with a greater facing-the-viewer bias (Heenan & Troje, 2014, 2015). This tendency to perceive more frequently ambivalent stimuli as approaching than as facing away from the ego may be in line with the reported findings. Indeed, individuals with anxiety-related personality traits may perceive the future imminent, as if it would move toward them.

Finally, a future-oriented thinking has been proposed to be highly functional, because future events can typically be acted on, whereas past events cannot (Caruso et al., 2013; Horwich, 1987). Representing future events as close may in fact prepare individuals to approach, avoid, or otherwise cope with them. The present results indicate that anxiety, which is often characterized by a sense of doubt and vulnerability about future events, brings future prospects close to the present. On the contrary, depression, which is often characterized by concerns regarding the ability to manage problematic aspects based on perceived failures in the past, shrinks the typical attentional focus on the future. In this sense, the functional propensity of facing the future may be highly corrupted in anxiety and depression. These results suggest, therefore, that clinicians should draw new attention to the role of psychological distance in psychopathology as well as in the psychotherapeutic process and outcome.

To conclude, the present study shows that the common tendency to perceive the future as psychologically closer than the past is exaggerated in individuals with anxiety-related personality traits, whereas this asymmetry drastically shrinks in individuals with depressed-related personality traits. Whether this distorted temporal perception originates from an altered sensorimotor functioning in space and time is a challenging question deserving empirical investigation.

CHAPTER 12

Discussion of part II:

TIME IN THE HUMAN MIND:
THE FLIP SIDE OF SPACE?

12.1. Summary of the second part of the thesis

The second part of this thesis investigated whether prior sensorimotor experience influences the spatial representation of time in four different studies.

In particular, in **Chapter 8**, we explored the influence of multiple directional sensorimotor routines, such as finger counting and reading habit, in the mapping of S-Time (i.e., overlearned sequences) on the bodily space. Bilingual participants reading either from left-to-right or from right-to-left were required to perform a finger-mapping compatibility task in three experiments to explore the spatial representation of numerical (digit numbers and number words) and non-numerical (days of the week, presented in Hebrew and in English) ordered sequences. Results showed that numerical information was preferentially mapped according to participants' finger counting habits, regardless of hand posture (prone and supine), number notation and reading habit. However, and critically, for non-numerical ordinal sequences, reading and finger counting directions both contributed to determine a preferential spatial mapping. These findings indicate, therefore, that the representation of ordered abstract information relies on multiple over-trained sensorimotor routines. More generally, these results highlight the capacity of our cognitive system to find the best way to flexibly represent abstract ordered information, by adjusting prior directional experience (i.e., finger counting, reading direction) to current requirements imposed by the task at hand.

In **Chapter 9**, we further explored the sensorimotor involvement in representational processing of S-Time (i.e., in this case of newly learned sequences). Specifically, participants performed a three-phase study. In the first phase, five random digits presented sequentially at the center of the screen had to be memorized in correct order by participants. In the second phase, all digits from 1 to 10 were randomly presented twice at the central position and participants had to decide whether a digit, i.e., the probe, was a member of the positive set or not. Finally, participants repeated the memorized sequence. Results showed that the search and the retrieval of serially-ordered information were mediated by spontaneous ocular movements. Specifically, recognizing middle items of the memorized sequence required longer inspection times and, importantly, a greater involvement of overt attentional resources, than recognizing the serially first-presented item and, to a lesser extent, the last-presented item. Moreover, serial order was found to be spatially encoded from left-to-right, as eye position during vocal responses deviated the more to the right, the later the serial position of the retrieved item in the sequence. These findings suggest that sensorimotor resources governing overt spatial attention mediate the scanning of serial order representation.

Subsequently, in **Chapter 10**, we explored the sensorimotor involvement in D-Time processing (i.e., past- and future-related words) along the sagittal space. In particular, participants were asked to categorize auditory words referring either to the past or to the future by means of whole-body single-step movements, directed backward or forward. By recording step movement kinematics, we showed that participants initiated faster steps backward in response to past- than to future-related words, whereas they initiated faster steps forward in response to future- than to past-related words. These results provide therefore striking evidence in support of the *moving ego* metaphor of time, according to which we would approach future events and leave them behind, as moving through a mental time line projected on a physical space. Moreover, these findings point to a critical role of the sensorimotor system in the representation of D-Time.

Finally, in **Chapter 11**, we explored the possible effects of emotion and sensorimotor experience on the representation of I-Time (i.e., subjective distance of events in time). Specifically, we asked whether the systematic tendency to experience the future as psychologically closer than the past, derived from our experiential movement through time, is altered in people who have slower walking speed and distorted motion perception, i.e., anxious and depressed individuals. Results indicated that individuals with anxiety-related personality traits showed an exaggerated tendency to perceive the future as psychologically closer than the past, whereas this tendency was drastically shrunk in individuals with depression-related personality trait. This study, therefore, indirectly suggests that an altered sensorimotor functioning might exert a decisive influence on the representation of temporal distance.

12.2. A conciliation of ATOM and MNL proposals

As discussed in the general introduction of the thesis (**Chapter 1**), two main proposals have been advanced to account for space-time interactions observed in humans. On the one hand, the ATOM (Bueti & Walsh, 2009; Walsh, 2003) proposal maintains that space and time are coupled metrics for action, with their common representation as "magnitude". Critically, these dimensions would be processed by areas in the human brain that are also involved in sensorimotor transformations for action, i.e. the parietal lobes. In fact, the development of magnitude processing is closely linked to motor activity, such as reaching, grasping and manipulating of objects. Hence, a great importance of sensorimotor experience is attached to ATOM.

On the other hand, the MTL proposal suggests that space-time interactions occur because visuospatial attention is needed for orienting the mind's eye through representation of temporal information. Hence, the role of spatial attention would be crucial for the MTL account, because it might be the medium for accessing and manipulating these spatial representations, in line with the view that parietal spatial maps are "culturally recycled" (Dehaene & Cohen, 2007).

But do predictions from one account exclude predictions from the other? Results from **Chapter 8**, **Chapter 9** and **Chapter 10**, suggest that the answer to this question is likely to be no. Overall, these studies indicate that prior sensorimotor experience might be crucial in the involvement of visuospatial attention during temporal processing. We propose, therefore, that both sensorimotor experience and visuospatial attention may shape the representation of time, although the role of each one would be crucial at different stages of processing.

12.3. Prior sensorimotor experience triggers attention toward the spatial representation of time

In this section, we will try to argue that the contribution of the sensorimotor system is central for the development of time representation because it triggers preferential directions of sensorimotor mapping. Critically, learning to program, control and coordinate actions in a spatiotemporal direction would induce consistent shift of attentional resources (i.e., covert and overt) toward certain portions of space in a given time. Action guidance does, indeed, require selective spatial attention. Considering, for instance, a child who learns to walk: he/she will need to program and control actions along spatiotemporal coordinates, and to move his/her body forward, in space and in time; in doing so, his/her attention will be also moved forward, step by step, to explore the surrounding environment and to provide the proper feedback of the ongoing action. In turn, attentional resources would follow a preferential spatiotemporal direction that would be consolidated by sensorimotor practice. Sensorimotor experience, therefore, would shift attention toward a preferential direction of the space-time continuum. The representation of time on internal spatial coordinates would consequently be grounded on external space, with the direction of this mapping that would be shaped by the direction of sensorimotor experience. Visuospatial attention would be, in turn, involved in searching along this internal continuum, when individuals process temporal information.

In short, sensorimotor practice along a specific spatiotemporal direction would consolidate the allocation of attentional resources toward preferential directions in both external and internal space. Such explanation would well fit with the Premotor theory of attention, according to which spatial attention is the consequence of the activation of the motor system (Rizzolatti, Riggio, Dascola & Umiltà, 1987; Rizzolatti & Craighero, 1998). Reaching, grasping and eye-movements, indeed, do all trigger shifts of attention (e.g., Craighero, Fadiga, Rizzolatti & Umiltà, 1999). In particular, the Premotor theory maintains that the activation of areas devoted to the programming and to the control of movements would be responsible for spatial attention. In fact, neuroimaging studies showed that the programming of eye movements toward a certain location of the space activates the same fonto-parietal network involved in covert attention (Corbetta et al., 1998; Nobre et al., 2000). In this sense, preparation of movements in space would shift attention in space, with a particular emphasis on the oculomtor system in having a privileged role on the control of selective spatial attention (Rizzolatti, Riggio & Sheliga, 1994; see also Craighero, Carta & Fadiga, 2001; Craighero, Nascimben & Fadiga, 2004). This is in line with the involvement of the parietal lobe in space-time interaction and with the primary role of reading and writing habits (i.e., two oculomotor practices) in establishing a preferential direction for the representation of D-Time and S-Time series, as also reported in **Chapter 8** and **Chapter 9**.

In fact, learning to read begins with the child forming an arbitrary association between selected aspects of printed words and their spoken counterparts. This process moves forward sequentially in space: it follows a certain order, piece by piece (e.g., letter by letter, syllable by syllable or words by words, etc.), and requires a fine spatiotemporal synchronization of meaning and action (e.g., see Reichle, Pollatsek & Rayner, 2006). Consequently, during learning and through experience, the oculomotor system is trained to scan visual information serially, with the scanning of mental representation that would follow such spatiotemporal order. Moving rightward in space in Western languages would be related with “moving” later in time, reinforcing an association between “before” and the left space and between “later” and the right space (see Casasanto & Bottini, 2014). Similarly, learning to write (i.e., handwriting) is governed by spatiotemporal rules, that in this case also involve the programming and motor control of manual actions (Van Galen, 1991; see also

Goodnow & Levine, 1973). In this sense, the acquisition of reading and writing, practices governed by tight spatiotemporal associations, would reinforce sensorimotor tendencies along a specific spatial direction. This sensorimotor experience would, in turn, provide the ground for representing and exploring the mental continuum onto which temporal order is grounded. This explanation might parsimoniously account for the overt attentional involvement in serial order processing reported in **Chapter 9**.

A similar argumentation holds for finger counting routine and, thus, for the effects reported in **Chapter 8**. Indeed, even considering the huge individual and cross-cultural variability in finger counting habits (Bender & Beller, 2011), these routines can be considered as universal since they require an embodiment of serial order. For instance, a certain motor action should be programmed and performed (e.g., extending one's own finger) and be linked to a certain ordered information (e.g., the number "one"), with this process that is repeated serially through bodily space (e.g., one's own hand) and through time (i.e., elements to be counted). Again, extending fingers in a specific order to count would also serially shift attentional resources in space and time, and would establish a preferential space-time representation. The same explanation can account as well for findings of **Chapter 10**, with a critical contribution of spatiotemporal tendencies involved in everyday walking behavior on the representation of D-Time.

Finally, a speculative interpretation of results reported in **Chapter 11** points to the possibility that altered sensorimotor experience in walking may distort the subjective feeling of temporal distance. In this case, indeed, an altered perception of motion may bias humans to distribute unequally attentional resources toward their past and future.

12.4. The functional need for mapping time on space

Even considering its centrality in the physical world, is there any advantage in representing temporal information along (internal and external) spatial coordinates? The need for this spatialization of time has been accounted for by the conceptual metaphor theory (Lakoff & Johnson, 1999) only in general terms, by suggesting that processing time as space may help humans to organize an abstract concept onto a more concrete domain. We propose that the specific need for this spatialization is that temporal distinctiveness might take advantage of spatial distinctiveness (see for a discussion Rinaldi, Gallucci & Girelli, 2015). Representing ordered information on the same spatial location, indeed, might not be the most parsimonious strategy at all. Otherwise, linking distinct temporal information to distinct ordinal spatial position would probably promote the representation of the sequence itself, helping encoding, storage, manipulation and, in some circumstances, even action related to the processed information (see **Chapter 9**). Consequently, spatial distinctiveness would prevent representational overlap of the elements to be processed, explaining therefore the early spread of temporal processing to space processing.

CHAPTER 13

General discussion:

EXPERIENCE GROUNDS HUMAN COGNITION OF SPACE AND TIME

13.1. Space and time in the human mind: a never-ending story

This doctoral thesis concerned the human sense of space and time, and its connection with sensorimotor experience. Space and time are fundamental and necessary dimensions to our understanding of the outside world: it seems almost impossible to conceive of what our experiential world might be like in the absence of space and time because, after all, real events always happen in space and time. Historically, there have been many attempts to grasp how our mind arranges sensory experience in a spatial and temporal framework. These attempts reached their culmination in the eighteen century, when the debate between the Leibnizians and the Newtonians, concerning the status of space and time, was resumed by Kant. Since then, philosophers and scientists have been captivated by understanding the way in which our mind constructs the experience of space and time. Nevertheless, it is only in recent years that researchers have raised empirical questions about the other way round, by exploring how sensorimotor experience may affect the human sense of space and time (Barsalou, 2008; Wilson, 2002). In fact, the brain's modal systems for perception (e.g., vision, audition) and action (e.g., movement, proprioception) can be crucial in shaping the human sense of both space and time. Accordingly, scattered evidence has recently showed that the perception of space and time can be shaped by the body's relation to the environment (see **Chapter 1**).

On these grounds, the present doctoral thesis attempted to provide some answers to one of the major mysteries in the study of human cognition: how the mind constructs the sense of space and time from experience. In particular, this thesis investigated some central questions on this long lasting debate, such as: can the human sense of space and time be sought in experience? What is the relationship between space and time in the human mind?

The first part of the thesis explored whether prior directional sensorimotor experience shapes the allocation of attentional resources in space, and whether situational requirements might further constrain visuospatial functioning. Findings from two studies (**Chapter 3** and **Chapter 4**) showed that the biological predisposition to overestimate the left side of the space (**Chapter 2**), due to the supposed right hemisphere dominance for visuospatial processing, can be modulated by sensorimotor experience and, specifically, by directional scanning associated with language processing (i.e., reading and writing). Two additional studies (**Chapter 5** and **Chapter 6**) unveiled that visuospatial attention can be further modulated by situational factors (i.e., current constraints imposed by task demands).

It was proposed, therefore, a hierarchical relationship between biological, cultural and situational factors in orienting attention in space (**Chapter 7**).

Since space and time are supposed to be tightly coupled in the human mind by motor actions, the second part of the thesis investigated whether sensorimotor experience may also influence the spatial representation of time. In four studies (**Chapter 8**, **Chapter 9**, **Chapter 10** and **Chapter 11**), it was demonstrated that prior directional sensorimotor experience in space (e.g., reading and writing, finger counting, locomotion) affects the processing and the representation of temporal information. Hence, it was suggested that sensorimotor practice along a specific spatiotemporal continuum would consolidate the allocation of attentional resources toward preferential directions in both external and internal (i.e., mental) space, influencing consequently the representation of time in the human mind (**Chapter 12**).

Overall, the present doctoral thesis indicates that the sense of space and time are not simply forms of *a priori* intuition, but rather they can be obtained through sensorimotor experience. Our bodily experience in space and time gives specific shape to our sense of space and time, by inevitably tangling up these two dimensions.

13.2. The role of sensorimotor experience in grounding the sense of space and time

Are time and space attributes of the physical cosmos, as suggested by modern physics, or are they dependent on the relations between experiential events, and hence not primarily an attribute of the world, but a consequence of it, i.e., an abstraction of the physical world? There will never be a final answer to this question. What this thesis adds to this debate, however, is that sources of the sense of space and time can be found in sensorimotor learning and experience. Space and time are coupled metrics for actions, as in everyday life our bodies move through a continuum in which these dimensions are rarely segregated (Bueti & Walsh, 2009). Experiencing motion through this continuum, therefore, would inevitably affect human perception and representation of space and time.

In particular, when actions are frequently repeated and become habitual routines, human perception of space and time must be shaped accordingly. Indeed, reading, writing, finger counting and walking, do all require a fine coordination of our sensorimotor system in both space and time (see **Chapter 7** and **Chapter 12**). When this spatiotemporal synchronization of actions becomes a routine, our perception and representation of space and time inevitably change, inasmuch as once humans are exposed to such practices, they accumulate a preponderance of tendencies to move in space and in time along a preferential direction. This sensorimotor experience along a preferential spatiotemporal continuum would play a causal role in determining how humans perceive and think about space and time. Studies presented and discussed in this thesis give empirical support to this proposition.

For instance, in learning to read and write, Western children have to program and control their sensorimotor system along a specific spatiotemporal direction, i.e., moving on a text line from left-to-right. In doing so, children start to learn that space and time are intrinsically associated to each other, with repetition of these practices that would reinforce the space-time association in long-term memory. As a consequence, this sensorimotor experience would be crucial in shaping people's perception about space. Hence, when Western people will have to search for a specific stimulus on a visual array, they will look for it by adopting the more canonical spatiotemporal routine derived from their prior sensorimotor experience, i.e., from left-to-right. Furthermore, this preferential processing of spatial information would be taken as the ground on which the flow of the more abstract domain of time is represented. Indeed, shifts through time would correspond to a rightward shift through space, as reading and writing also proceed temporally from left-to-right in Western cultures. A similar mechanism would also hold for finger counting and walking, because these two routines tightly link space and time along their own preferential spatiotemporal direction.

Where would be the best place in the brain for coding space and time by sensorimotor learning? The parietal cortex seems to be the ideal candidate for such coding. Indeed, it is likely that the strict coupling between space and time is found in the parietal cortex because of the need to encode space and time for action. The parietal lobes are directly involved in performing sensorimotor transformation for action and, crucially, in spatial and temporal processing (see for a review Bueti & Walsh, 2009). Accordingly, the parietal cortex might be the major candidate for integrating sensorimotor experience into our sense of space and time.

Overall, the present thesis supports the proposal that we learn about space and time through actions, and that associations between space and time are made possible by the same actions performed in the physical world (Bueti & Walsh, 2009; Walsh, 2003). In this sense, space and time in the human mind would be conceived as the proximal consequence of sensorimotor experience.

13.3. Moving from here and now: future directions

Why do people from different cultures behave differently? Are there any consequences for these behavioral cross-cultural differences on neural networks? These fascinating questions have been studied extensively in psychology by examining human cognitive and affective processes across cultures (see for a review Han & Northoff, 2008). Recent findings indicate that the functional and structural organization of the brain is highly sensitive to culturally contextualized behavior and life experience (Han & Ma, 2015). In fact, our environment and our experience powerfully constrain how genotypes give rise to behavioral phenotypes (Manuck & McCaffery, 2014). Since mental activity is underpinned by the neurobiology of the brain that, in turn, is shaped by experience (Han & Northoff, 2008), a cross-cultural neurocognitive approach is most needed in the study of the human sense of time and space. Cultural neuroscience is ideally suited to tackle the long-standing question regarding the extent to which brain functioning is determined by genetic background, i.e., nature, and by experiences, i.e., nurture.

Cross-cultural neurocognitive studies may therefore substantiate or disconfirm the alleged effects of reading and writing direction on hemispheric lateralization of fronto-parietal networks subserving visuospatial processing, as proposed by the IAVA hypothesis (**Chapter 7**). Furthermore, these studies may provide new insights on whether cultural experiences only modulate pre-existing and pre-established patterns of neural activity, or whether they can even determine the observed patterns of brain lateralization. In other words, they may shed light on whether these sensorimotor experiences are modulatory or constitutional. Indeed, cultural experience may induce possible epigenetic changes that can be delivered across generations (Han & Ma, 2015). In this sense, the lateralization of brain networks responsible for visuospatial attention may differ between cultures even prior of any “cultural” experience.

Such a cultural approach may also be well suited for investigating the role of situational factors on visuospatial processing. In particular, from a neurofunctional point of view, the temporal pole has been suggested to integrate sensory information and limbic inputs and to connect past experiences with material that is currently being processed (see for a review Han & Northoff, 2008). Hence, future studies should explore whether specific constraints imposed by the task at hand engage similar neural resources independently from cross-cultural variability. Although this may require complex experimental designs, these investigations might contribute to a better understanding of the interaction between biological, cultural and situational factors.

Contributions to the role of sensorimotor experience on the human sense of time might be various. First, rather than focusing on the time-space mapping *per se*, future studies should explore whether neural resources shared by sensorimotor processing, time perception and visuospatial attention are responsible for the embodiment of temporal concepts (**Chapter12**). This means directing attention not only to perceptual and motor neural networks dedicated to temporal processing, but also to those subserving space-time integration.

A second challenging question relative to the understanding of temporal concepts is whether different representations of time are governed by specific brain areas. For instance, future research should explore whether the internal and external representations of D-Time actually rely on an activation of egocentric or allocentric spatial frames of reference, respectively. Similarly, future studies may elucidate if the deictic center of D-Time representation refers to the (spatial) state of the body in the moment *now.*

Finally, although the present thesis indicates that the human sense of space and time are grounded in the sensorimotor system, it is not clear *how much experience* is necessary to let time be mapped on spatial coordinates. Future studies, therefore, are needed to enrich our understanding on the contribution of sensorimotor experience during development, in infancy and in early childhood. Indeed, few instants might be sufficient for human minds to intrinsically link space and time.

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Incontro

Queste dure colline che han fatto il mio corpo
e lo scuotono a tanti ricordi, mi han schiuso il prodigio
di costei, che non sa che la vivo e non riesco a comprenderla.

L'ho incontrata, una sera: una macchia più chiara
sotto le stelle ambigue, nella foschia d'estate.
Era intorno il sentore di queste colline
più profondo dell'ombra, e d'un tratto suonò
come uscisse da queste colline, una voce più netta
e aspra insieme, una voce di tempi perduti.
Qualche volta la vedo, e mi vive dinanzi
definita, immutabile, come un ricordo.
Io non ho mai potuto afferrarla: la sua realtà
ogni volta mi sfugge e mi porta lontano.
Se sia bella, non so. Tra le donne è ben giovane:
mi sorprende, e pensarla, un ricordo remoto
dell'infanzia vissuta tra queste colline,
tanto è giovane. È come il mattino, mi accenna negli occhi
tutti i cieli lontani di quei mattini remoti.
E ha negli occhi un proposito fermo: la luce più netta
che abbia avuto mai l'alba su queste colline.

L'ho creata dal fondo di tutte le cose
che mi sono più care, e non riesco a comprenderla.

Cesare Pavese (1936)