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Dissociation between the focal and orientation components of spatial attention in detection, discrimination and reading tasks

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Summary

In our daily life, attention plays a fundamental role in governing our visual experience. Indeed, every visual experience consists of an overwhelming amount of visual information reaching our visual system. Spatial attention allows us to select the relevant information, which is important for our goals, while ignoring the irrelevant information in our environment. However, spatial attention is not a unitary notion, but a multi-faceted concept comprised of different components. There are two distinct components that dictate how attentional resources can be allocated: an orientation component, which moves the attentional resources to relevant locations for further processing; and a focal component, which allows us to converge our resources on a limited space.

The present dissertation investigates the classical view of these two components of spatial attention, providing a characterization of both and their mutual relationship. Using a combination of behavioural and neuropsychological evidence, we investigated how these two components operate in different viewing conditions, with different temporal trends and different task demands. Finally, we examined how a deficit in the ability to adjust attentional focus can condition the reading process in brain-damaged patients.

By measuring the cue-size effect in healthy participants, the first set of studies characterizes how the focal component is deployed in the centre of the visual field. These studies show that, even if detectable in both exogenous and endogenous conditions, the facilitatory effect of the focal component is best revealed and more effective in exogenous conditions. Moreover, we elucidated the role played by the task demands and the stimuli used in evoking this facilitatory effect.

The second set of studies, always on healthy participants, further extends these findings by showing that the focal and the orientation components of spatial attention are independent of

each other, as displayed by their effects in different viewing conditions and with different temporal trends. The dissociation of these two components is evident not only in simple tasks, such as single letter detection or discrimination, but also in a more reading-related task, which consisted of discriminating one letter from others.

Following the completion of evidence gathering with healthy participants, the third set of studies investigates how a deficit in the control of focal component could be responsible for the substitution errors that brain-damaged patients affected by neglect dyslexia (ND) make in reading single words. Results showed that substitution errors occur depending on the difficulty of perceptually segregating letters from each other. A deficit in the control of focal component plays a main role in increasing this phenomenon by preventing the adjustment of the integration field necessary for identifying and reading each letter correctly.

Overall, this set of experiments illustrates the dissociation between the focal and the orientation components of spatial attention and suggests the existence of a causal link between the former and subsequent reading substitution errors.

Chapter 1 - Introduction

Attention is usually defined as the process through which, at a given moment, we enhance some information for further processing while inhibiting other stimuli present in our environment. Although everyone has an intuitive understanding of what "pay attention" means (reflected in William James's (1890) famous claim that "everybody knows what attention is"), attention is a very complex and multi-faceted function.

In the visual domain, attention plays a fundamental role in regulating our visual experience. Indeed, every time we open our eyes we experience an overwhelming amount of visual information. Despite this, we are still capable of understanding our visual world effortlessly. What seems to be an easy experience for us is actually a complex and ongoing process for our brain. Every visual experience requires the division of the continuous flow of visual information that is reaching our retinas, the selection of only the most relevant information, and the rejection of all other irrelevant noise. Visual attention is the key to this process: it is the mechanism that transforms looking into seeing (Carrasco, 2011). Moreover, visual attention can select different kinds of information: (1) spatial attention refers to the ability to direct and concentrate attention to a specific location in the environment; (2) feature-based attention refers to the ability to concentrate on specific aspects of objects in the environment, regardless of their location; and finally (3) object-based attention is guided by object structures (Carrasco, 2011).

Visuo-spatial attention has been the object of numerous studies, which showed that it can be deployed in various ways. For instance, visuo-spatial attention can be alternating (i.e. shifting attention and moving the focus between different locations), distributed (responding simultaneously to multiple locations) or selective (concentrating on one location in the environment while avoiding distractions both external and internal stimuli). The topic of the present thesis will be the visuo-spatial attention.

In the present chapter, I will firstly provide an overview of the most recent findings in the literature about visuo-spatial attention, by focusing on its two different components: the focal component and the orientation components. Finally, I will introduce a new hypothesis that predicts the independence of these two components from each other, and which constitutes the main theoretical framework of the present thesis.

1.1. Visuo-spatial attention as a multi-faceted process

Visuo-spatial attention can be defined as the mechanism that selects the most important information from among the many competing stimuli present in the environment; both our goals and the salience of the information surrounding us determine where and what we attend to. Visual attention selectively enhances the visual information processing of a specific attended location, while it inhibits the processing of others (He, Cavanagh & Intriligator, 1996, 1997).

This selective mechanism is deemed to be necessary due to the limit of our visual information processing system and our limited cognitive resources (Broadbent, 1958). How different stimuli compete for limited resources is demonstrated by behavioural, electrophysiological and neuroimaging studies (for a review see Desimone & Duncan, 1995; Beck & Kastner, 2009), which typically show that neurons with receptive fields at the attended location remain or become more active while others are suppressed, reflecting a greater resource allocation to the attended location.

Thus, the purpose of spatial attention is to allow us to maximize our performance by overcoming the visual system’s limited resources, thanks to the enhanced representation of relevant information and the simultaneously reduced representation of less relevant information. Nevertheless, nowadays it is clear that spatial attention is not a unitary notion, but a multi-faceted concept, which is comprised of different components.

First of all, visuo-spatial attention can be allocated to a specific location both by moving the eyes toward that location (overt attention) or without directing the gaze directly towards it (covert attention). Specifically, covert attention can be directed at more than one location at the same time, whereas overt attention can be directed at only one location at a time, since eye movements are necessarily sequential (Kowler, 2011). Therefore, overt attention usually guides our eye movements to the locations of the most relevant information. More interestingly, although the effects of covert and overt attention on perception are often similar, some studies have proved that exceptions are possible (e.g. Nakayama & Martini, 2011).

Secondly, attention can be allocated in two different ways, as originally described by James (1890): when the process is involuntary and passive we refer to it as exogenous attention, whereas when it is active and voluntary it is known as endogenous attention. Exogenous attention, which is often linked to abrupt visual changes, is characterized by a minimum use of resources and relative independence from working memory, whereas endogenous attention is characterized by more flexibility and central control and higher cognitive load (e.g. Jonides, 1980, 1981; Posner 1980). A further difference between exogenous and endogenous attention is represented by their temporal nature, with exogenous attention being more transitory than endogenous attention (Busse, Katzner & Treue, 2008). Whereas the former is characterized by short activation time and quick decay, the latter takes longer to be activated and its decay is slower (e.g. Liu, Stevens & Carrasco, 2007; Muller & Rabbit, 1989; Remington, Johnston & Yantis, 1992). The different temporal characteristics of these two attentional systems suggest that they may fulfil different purposes, as proven by some studies which show the purely cortical nature of endogenous attention compared with the additional recruitment of subcortical processing in the case of exogenous attention (Robinson & Kertzman, 1995; Zackon, Casson, Zafar, Stelmach, & Racette, 1999). Indeed, even if exogenous and endogenous attention share some similar effects, they are also characterized by some unique effects (e.g. Hikosaka, Miyauchi, & Shimojo, 1993; Suzuki & Cavanagh, 1997). For instance, some studies demonstrate that exogenous attention has greater effects than endogenous attention in visual search tasks (Briand, 1998; Briand & Klein, 1987), and that endogenous attention impairs temporal order judgments, whereas exogenous attention improves them (Hein, Rolke & Ulrich, 2006). Furthermore, other studies show that the attentional benefits of endogenous attention increase as cue validity increases, whereas the benefits and costs of exogenous attention are comparable across the range of cue validities (Giordano, McElree & Carrasco, 2009).

Finally, the allocation of attentional resources to a location in the space involves two distinct processes: the orientation process, which shifts attentional resources to the relevant locations for further processing; and a focusing process, which acts as a magnifying lens and allows us to concentrate our resources selectively on a limited space within the environment, while ignoring the rest of it (e.g., Chun, Golomb, & Turk-Browne, 2011). We refer to the former as the "orientation component" and at the latter as the "focal component".

Although the distinctions between "endogenous vs exogenous" and "covert vs overt" have both been studied extensively in terms of behavioural effects and neuro-functional mechanisms (e.g., Corbetta & Shulman, 2002; Kincade, Abrams, Astafiev, Shulman & Corbetta, 2005), the same cannot be said of the focal and orientation components; in fact, nowadays it is still unclear if these two components constitute different and independent mechanisms, or if they are different features of the same attentional mechanism or, lastly, if the focusing process constitutes just one part of the orienting process.

1.2. The orientation component

The orientation component was defined by Posner (1980) as the alignment of attention with a source of sensory input or with an internal semantic structure stored in memory. By using his classical cueing paradigm, Posner (1980) showed that detection or discrimination of a target is more accurate, faster, or both, when the target appears at a cued location than when the location is uncued. Generally, in this paradigm (see Figure 1.1. for an example) participants are required to maintain their fixation on a central mark and not to shift their gaze, while they undergo a task requiring them to press a key as fast as possible at the appearance of a target stimulus in the periphery of the visual field; the appearance of the target can be preceded or not by a central or peripheral cue. This paradigm allows us to compare the performance of different conditions in which attention is directed to either the specific target location (cued condition), away from the target location (uncued condition), or distributed across the visual field (neutral condition). Shorter reaction times at cued locations, with respect to uncued locations or to the neutral condition, are interpreted as an advantage related to the spatial attentional processing, whereas longer reaction times at the uncued locations are usually interpreted as the cost associated with the spatial allocation of selective attention (Posner, 1980; Castiello & Umiltà 1990).

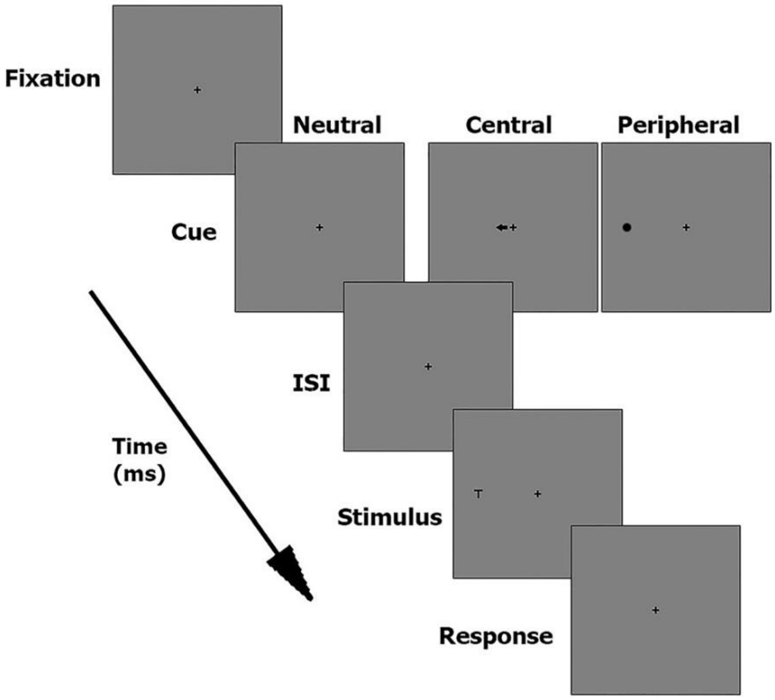

Figure 1.1. Example of a trial in the Posner paradigm. Participants can perform either a detection or a discrimination task on the target stimulus, which is presented at the periphery of the visual field. After the fixation screen, the target appearance can be preceded by a central cue, a peripheral cue or a neutral cue. The cue can be either valid (same location of the target stimulus) or invalid (different location of the target stimulus).

Depending on the purpose of the experiment, two different cue types can be used to direct the participant's covert attention: a central and symbolic cue is typically used to engage the voluntary orienting of attention (e.g. arrows which point to particular locations of the visual field), whereas a peripheral cue is generally used to engage it involuntarily (e.g. the abrupt onset and offset of a dot at the target location). Both cue types typically have similar effects on the observer's performance, by enhancing it at the cued location while impairing it at the uncued location, as compared to the neutral condition (Pestilli & Carrasco, 2005). Even though the events that capture attention are not always peripherally located, most of the studies on the orientation component used peripheral cues to orient attention and did not compare the effect of central and peripheral cues. In fact, only a few studies investigated the effect of different cues on the orientation component, suggesting that the effects of central and peripheral cues could differ in temporal and spatial terms (e.g., Carretié, Albert, López-Martín, Hoyos, Kessel, Tapia & Capilla, 2013). Posner and Cohen (1984) have described an additional effect that is usually detected by using this paradigm: the inhibition of return. After attention has been directed or allocated to a specific location, it is possible to detect a delay in responding to stimuli later displayed at the same location. A possible explanation of this inhibitory aftereffect is that the inhibition of locations already explored could promote the direction of the attention towards novel locations and may facilitate novelty-seeking, foraging and other search behaviours (e.g. Posner & Cohen, 1984; Wang & Klein, 2010).

Because of its simplicity, the Posner paradigm or its variants are widely used to investigate the effect of orienting attention on different performance measures and in different conditions. For example, it was showed that for attended stimuli the contrast thresholds (e.g. Solomon, 2004; Carrasco & McElree, 2001; Solomon, Lavie & Morgan, 1997), as well as the discrimination thresholds (e.g. Lee, Koch & Braun, 1997) are enhanced. Moreover, orienting attention seems to influence performance in visual search tasks (e.g. Carrasco & Yeshurun, 1998; Morgan, Ward & Castet, 1998), in acuity tasks (e.g. Yeshurun & Carrasco, 1999), in texture segmentation tasks (e.g. Gurnsey, Pearson & Day, 1996) and in crowding tasks (Yeshurun & Rashal, 2010; Huckauf &

Heller, 2002). The Posner paradigm is also extensively used in neuroimaging (PET, fMRI and EEG) studies in order to reveal the neural substrate of orienting attention. Typically, these studies have demonstrated that orienting attention is associated with activity in the right posterior brain areas, including the superior parietal lobe, the temporal parietal junction and the frontal eye fields (Posner, 1980; Corbetta, Kincade, Ollinger, McAvoy & Shulman, 2000). Activation in the right intraparietal sulcus was also observed by using variants of Posner's paradigm (e.g. Nobre, Sebestyen, Gitelman, Mesulam, Frackowiak & Frith, 1997). With regards to electrophysiological evidence, ERP studies (Posner & Gilbert, 1999; Talsma, Slagter, Nieuwenhuis, Hage & Kok, 2005; Fu, Greenwood & Parasuraman, 2005; Wang, Wu, Fu & Luo, 2010) highlighted that the P1 and N1 are the most common components modulated by orienting attention during visual attention tasks: compared with targets in invalid trials, targets in valid trials usually elicit larger P1 and smaller N1 components over the posterior scalp areas. In addition, some studies (Mangun, Hillyard & Luck, 1993; Wang et al., 2010) reported larger N2 amplitude elicited by targets in valid cue trials relative to invalid cue trials and larger P3 elicited by targets in invalid cue trials relative to valid cue trials.

Taken together, these results suggest that attending to the target location both enhances detection and discriminability of finer details by improving the information processing at that specific location, and thus improves the evoked neural response associated with it (Carrasco, 2011).

A very common manipulation of Posner's classic paradigm, which can influence the attentional effect on observers' performance, refers to the stimulus onset asynchrony (SOA) between the appearance of the cue and the target. Indeed, SOA manipulation allows us to investigate the temporal trend of the orientation component. It was observed that peripheral cues orient spatial attention to the peripheral visual field more rapidly (around 100 ms) and that they decay quicker than central symbolic cues do (around 300 ms; Posner & Cohen, 1984; Muller & Rabbit, 1989). Furthermore, some authors (Epstein, Conners, Erhard, Marsh & Swanson, 1997) have argued that the most important factor in distinguishing between an automatic (exogenous) and a voluntary (endogenous) allocation of attention is indeed the duration of the SOA, with shorter SOAs evoking an exogenous and automatic orienting process longer SOAs eliciting a more voluntary and endogenous control of orientation component.

After Posner (1980) and Jonides (1981) first proposed that the orientation component is controlled both exogenously and endogenously, this distinction was then studied both in terms of the behavioural effects and neuro-functional mechanisms (e.g., Kincade et al., 2005). Endogenous attention and exogenous attention can cause similar effects on performance in many tasks; however, they also show some distinctive effects (e.g. Hikosaka et al., 1993; Suzuki & Cavanagh, 1997; Briand, 1998; Briand & Klein, 1987; Friesen & Kingstone, 2003). Indeed, the independent and typical effects of endogenous compared with exogenous orientation have been demonstrated in various tasks such as simple detection, target localization and saccadic responses (e.g. Theeuwes, 1991; Coull, Frith, Buchel & Nobre, 2000; Berger, Henik & Rafal, 2005). For instance, some studies revealed that endogenous attention has a greater effect on performance under high-noise conditions, whereas exogenous attention affects performance in both low- and high-noise conditions (Lu & Dosher, 1998; 2000). Furthermore, exogenous attention improves performance by signal enhancement (e.g., Lu & Dosher, 1998; Dosher & Lu, 2000), whereas endogenous attention is only mediated by external noise reduction (e.g., Lu, Liu & Dosher, 2000; Ling & Carrasco, 2006). Taken together, these results seem to suggest that exogenous and endogenous orienting components are mediated by dissociable and autonomous mechanisms. This has been supported by neuro-functional studies, which proved the existence of an anatomical separation in devoted neural systems of the two components. For instance, different ERP studies showed that whereas exogenous attention is dominant in the earliest stages of processing (i.e. P1 component), endogenous attention dominates the later stages (i.e. P300 component). Endogenous attention may also affect the earlier stages of processing (i.e. N1 and P1 components), but in a different way than exogenous attention (Hopfinger & West, 2006; Clark & Hillyard, 1996; Hopfinger & Mangun, 2001). Neither exogenous nor endogenous orientation have ever been found to modulate the C1 component, which constitutes the earliest visually evoked cortical component (e.g. Di Russo, Martinez & Hillyard, 2003). Differences between the brain areas involved in the two types of orienting have been reported by recent neuroimaging studies, which proved that these two orienting mechanisms are mediated by separate neural systems (e.g. Mayer, Dorflinger, Rao & Seidenberg, 2004; Mort, Perry, Mannan, Hodgson, Anderson, Quest, McRobbie, Husain & Kennard, 2003; Kincade et al., 2005). In particular, a new model was proposed in which endogenous attention depends on the superior frontal cortex and intraparietal sulcus, core regions of the dorsal fronto-parietal attention network, whereas exogenous attention depends on the temporo-parietal cortex, the inferior frontal cortex and part of the dorsal network, and is largely lateralized to the right hemisphere (Kincade et al., 2005; Corbetta & Shulman, 2002).

Overall, the available evidence on the orientation component of visuo-spatial attention suggests that orienting attention to the target location enhances both the behavioural performance and the evoked neural response associated with it, and that exogenous and endogenous orienting represent two attentional mechanisms that can affect information processing in distinct ways.

1.3. The focal component and the cue-size effect

Different objects have different shapes and sizes, so it is possible that once attention has been oriented, it will also be adjusted to the size of the attended object. The focal component of spatial attention refers to this ability to adjust the size and the shape of the attentional focus, with a subsequent increase of the efficiency of the processing of specific locations or objects within it (He et al., 1997). Clearly, this ability is in contrast with the ability to allocate attention equally across all possible locations, i.e. distributed attention (Jonides, 1981).

Attentional focus has been described either as a spotlight (Posner, 1980) or a zoom-lens (Eriksen & Yeh, 1985; Eriksen & St. James, 1986), which in both cases enhances the processing of visual stimuli within a circumscribed region of space. The spotlight metaphor (Posner, 1980) claims that attentional focus is characterized by three main properties: it moves from one location to another, it has a specific size, and that size can vary only according to retinal eccentricity, not to central control. The zoom-lens model (Eriksen & Yeh, 1985; Eriksen & St. James, 1986), by contrast, states that attentional focus is more like a lens of variable size than a rigid spotlight, and that it is under both central and external control. This last model also predicts the existence of an inverse relation between the size of the attentional focus and the efficiency of processing within it, i.e. the cue-size effect (e.g. Castiello & Umiltà, 1990).

Several studies have shown that people can adjust the size of their attentional focus voluntarily in accordance with task demands, increasing processing efficiency as the size of their focus decreases (Castiello & Umiltà, 1990, 1992; Eriksen & St. James, 1986; Usai, Umiltà & Nicoletti, 1995; Benso, Turatto, Mascetti & Umiltà, 1998; Egeth, 1977). On the contrary, when attention is equally distributed across the entire visual field there is a corresponding loss in processing efficiency and spatial resolution (Castiello & Umiltà, 1990, 1992; Eriksen, 1990; Eriksen & Murphy, 1987; Eriksen & St. James, 1986; Eriksen & Yeh, 1985). Typically, in experiments of focal attention (see Figure 1.2. for an example) participants are required to concentrate their attention on a cued region of different sizes and to respond as fast as possible to a stimulus shown within it. As a result, participants are usually faster and more accurate within smaller cued regions, proving the existence of an inverse relationship between the size of the attentional window and processing efficiency (Castiello & Umiltà, 1990, 1992; Egeth, 1997; Eriksen & St. James, 1986).

Traditionally, the focal component of spatial attention was rarely considered independent of orienting; in fact more often it was considered just a part of, or sometimes even confounded with, the orientation component. Some early studies (Castiello & Umiltà, 1990, 1992; Stoffer, 1991) demonstrated that when observers have to orient their attention to a location and then focus on a target, they gained a temporal advantage in detecting the target after a small cue was presented for a long SOA (500 ms), whereas this temporal advantage is not detectable for very short SOAs (i.e. 40–50 ms). This suggests an independence between the two components of visuo-spatial attention, with orienting being faster and focusing arriving later. However, because these studies primarily investigated the focal component solely in the periphery of the visual field, they provided only indirect evidence about the independence of the two mechanisms; indeed they did not compare the focal and the orientation components directly, simply inferring the role of the orientation component from the delay in the deployment of the first one.

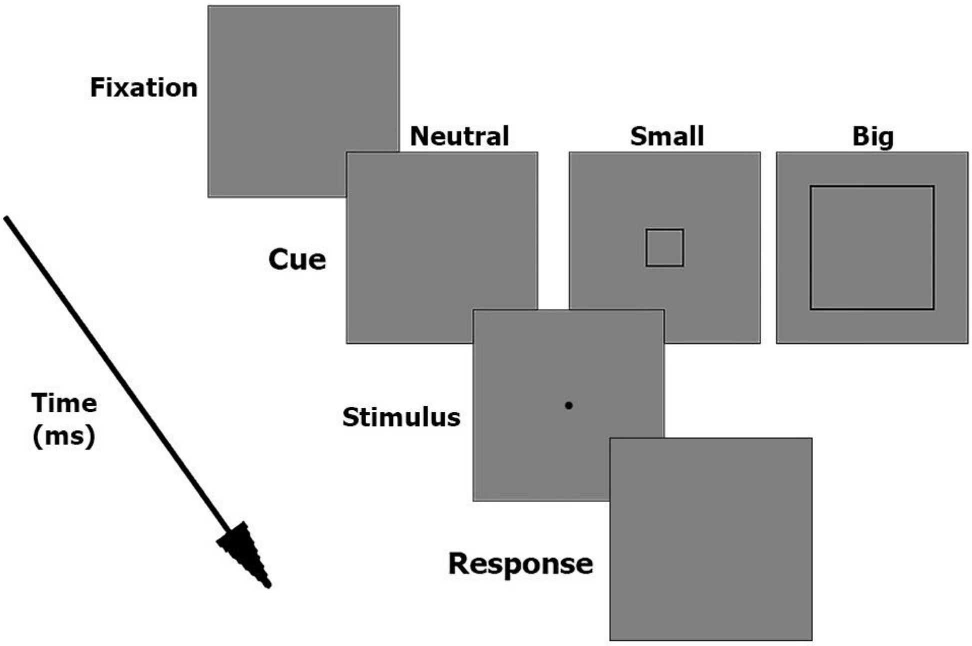

Figure 1.2. Example of a trial procedure in a focal attention paradigm. Participants can perform either a detection or a discrimination task on the target stimulus, which is usually presented at the centre of the visual field. After the fixation screen, the target appearance can be preceded by a small cue, a big cue or a neutral cue (baseline condition).

In an attempt not to confound the focal and the orientation components, most studies on the focal component have tried to examine it in isolation, by manipulating the SOA between the appearance of the cue and the target, in order to examine its temporal trend. For instance, Maringelli and Umiltà (1998) showed that, in the case of foveal vision, the attentional benefit related to the presence of a smaller cue is present both for shorter (i.e. 100 ms) and longer SOAs (i.e. 500 and 700 ms). The authors also demonstrated that the inverse relationship between visual efficiency and the size of the attentional focus is present only if the different cue sizes are randomized across trials, whereas it disappears when different cue sizes are presented in a fixed sequence. This suggests that the focal component is automatically triggered by the appearance of a new object. However, the different effects of the random and blocked presentation could also reflect the intervention of a strategic component rather than the automatic component (Hawkins, Shafto & Richardson, 1988). Other studies (Turatto, Benso, Facoetti, Galfano, Mascetti & Umiltà, 2000; Benso et al., 1998) have suggested that the focal component is caused by two independent mechanisms: one automatic and exogenous, for short intervals (about 60–100 ms), and one voluntary and endogenous, for longer intervals. The first would automatically fit to a new object appearing in the visual field, while the second would maintain attention in the focused mode (Turatto et al., 2000). Finally, some studies have demonstrated that the duration of the focal component may be different in different visual conditions; indeed, even if the control of attentional focus can be deployed both in the centre and in the periphery of the visual field (Benso et al., 1998; Henderson, 1991), typically the focal component occurs at longer SOAs when it is employed in the periphery. These data have supported the hypothesis of low attentional focus efficiency when it is deployed outside the fovea, probably due to the poorer resolution of details in the peripheral areas of the visual field (Eriksen & St. James, 1986).

Beyond the characterization of its temporal trend, other studies have investigated whether attentional focus can be split simultaneously in different locations. Though some studies have found that the focal component can be split (Shaw & Shaw, 1977; Castiello & Umiltà, 1992; Müller & Findlay, 1987), most studies investigating this issue have claimed that attentional focus cannot be divided into discontinuous zones and that, instead, it has to be deployed in an unitary way (e.g. Eriksen & Yeh, 1985; McCormick & Klein, 1998; Usai et al., 1995; Jefferies & Di Lollo, 2009). Usai and colleagues (1995) highlighted also that not only can attentional focus not be split, it cannot be adjusted to all possible shapes either. They found that attention cannot be allocated flexibly to irregular figures such as hexagons, rhombi and polygons.

Taken together, these results propose that narrowing attentional focus around a specific object or location enhances the detection and discrimination of stimuli within it, both in the centre and at the periphery of the visual field, and that the focal component can be deployed both exogenously and endogenously.

Though the behavioural effects of the focal component have been well described, only a few studies try to identify and isolate the neural substrate of this component. For instance, some authors (Brefczynski & DeYoe, 1999; Müller, Bartelt, Donner, Villringer & Brandt, 2003) have demonstrated that the level of neural activity in multiple retinotopic visual areas is inversely correlated with the size of the attended region and that the extent of the activated primary visual cortex increases with the size of the attended region. This observed inverse correlation of neural activity with processing speed and accuracy was interpreted as physiological evidence of the zoom-lens model (Müller et al., 2003). However, it has to be mentioned that other studies have shown that the deployment of the focal component activates other areas beyond the primary visual cortex. Indeed, Chen and colleagues (Chen, Marshall, Weidner & Fink, 2009) found that the left anterior intraparietal sulcus (IPS), the right middle temporal gyrus, the right superior occipital gyrus and the right superior parietal cortex are also activated, suggesting that the right posterior temporal–occipital–parietal system, which is known to be crucial for the control of spatial attention, is involved in the control of focal component too. Another important role in the deployment of the focal component seems to be played by the insula, the anterior part of which in particular (Nelson, Dosenbach, Cohen, Wheeler, Schlaggar & Petersen, 2010).

Few studies have investigated the ERP responses associated with the focal component (Luo, Greenwood, Parasuraman, 2001; Fu, Caggiano, Greenwood & Parasuraman, 2005; Song, Li, Luo, Du & Ji, 2006; Niu, Wei & Luo, 2008). Despite common agreement about the modulation of the P1 and N1 by the focal component of visuo-spatial attention (but see also Eimer, 2000 for absence in modulations of sensory-evoked P1 and N1 components), differences in the direction of the modulation have been found. Some studies claim that the amplitude of the P1 component increases with cue size, whereas the amplitude of the N1 component decreases as cue size increases, (Luo et al., 2001; Niu et al., 2008). However, other studies (Fu et al., 2005; Song et al., 2006) have found that smaller cues elicit both larger P1 and N1 components and that P2 amplitude increases as the size of the cue increases. These last findings suggest that changes to the P1 and N1 components may reflect the additional computations required for changing the spatial scale of attention to the appropriate element size, in order to facilitate target discrimination or the broadening of the spatial gradient of attention. However, since none of these studies specifically took into account the two modalities with which the focal component can be deployed (exogenously vs endogenously), these contrasting results may also be explained by differences in the voluntary and involuntary deployment of the focal component. In fact, only one study (Wang et al., 2010) tried to investigate this issue, showing that the modulation of the P1 component depends on the temporal constraints with which the focal attention is deployed. Specifically, when the focal component is exogenously deployed the amplitude of the P1 component increases as the cue size decreases, whereas larger P1 components are elicited by larger cues compared to the smaller ones when the focal component is endogenous.

Overall, the available evidence on the focal component of visuo-spatial attention suggests that narrowing the focus of attention enhances both behavioural performance and the evoked neural response associated with it. Furthermore, the literature about attentional focus seems to highlight that the temporal trend of attentional focusing includes a primary period during which the attentional focus is automatically triggered by the abrupt onset of the cue (e.g. Maringelli & Umiltà. 1998; Turatto et al., 2000), and a secondary period in which the focus of attention is actively maintained (e.g. Benso et al., 1998; Turatto et al., 2000).

1.4. Concluding remarks and specific aims

In the last few decades, several studies have investigated how the focal and the orientation components of visuo-spatial attention are deployed under different time constraints. However, most of these studies examined the effect of either the orientation or the focal component in isolation, without clarifying the relationship between them, and without taking into account how different factors such as task demands and eccentricity can affect their deployment. For instance, even though attention can be captured by events both centrally and peripherally located, most of the studies on the orientation component used only peripheral cues to orient attention and did not investigate the orientation component in the centre of the visual field. By contrast, most of the studies on the focal component investigated it exclusively in the centre of the visual field. Thus, we are still far from a complete characterization of either the focal or the orientation component, nor of their relationship to each other.

For this reason, the following chapters will provide a characterization of both components and their relationship through a series of studies; I will provide evidence of the hypothesis that orienting and focusing reflect two different mechanisms that operate independently and with different modalities. To this aim we have used different paradigms, i.e. detection tasks, discrimination tasks and tasks that require identifying a stimulus flanked by other stimuli.

In Chapter 2, I will illustrate how the focal component works in foveal vision under different task demands. I aim to explore whether the attentional effect is strictly related to the task or if it is independent of it.

In Chapter 3, I will describe the use of different paradigms to obtain evidence that the focal and the orientation components are two independent processes. I will investigate how these two mechanisms operate in different viewing conditions, with different temporal trends and different task demands.

In Chapter 4, I will investigate how the focal and orientation components reduce crowding and critical spacing differently in central and peripheral vision. At this point, I will also link my investigation about the independence of these two components to the reading process.

Finally, in Chapter 5, I will investigate how a lack of control of focal component could be responsible for substitution errors in reading, by describing a brain-damaged patient affected by unilateral spatial neglect (USN) and neglect dyslexia (ND).

Chapter 2 - The effect of task demands on the focal component in central vision

2.1. Aim of the study

The focal component and its deployment in foveal vision have been investigated by various studies (e.g. Maringelli & Umiltà, 1998; Benso et al., 1998; Turatto et al., 2000). As discussed in Chapter 1, these studies suggested that the focal component can be deployed exogenously, as when it is automatically triggered by the abrupt onset of the cue (e.g. Maringelli & Umiltà. 1998; Turatto et al., 2000) or endogenously, as when it is maintained actively (e.g. Benso et al., 1998; Turatto et al., 2000).

However, most of these studies considered the focal component as just one part of the orientation process (and therefore they often confounded it with the orientation component); furthermore, they did not take into account the specific effect of the task demands. Indeed, it could be argued that the characteristics of the focal component (and also of the orientation component) can be revealed by using different task paradigms. Thus, it is possible that differences across studies may be related to the specific task chosen or to the confusion in disentangling the effects of the orientation and focal components. Indeed, whereas some studies used detection tasks (e.g. Benso et al., 1998; Maringelli & Umiltà, 1998), others used discrimination tasks (e.g. Egeth, 1977; Eriksen & St. James, 1986; LaBerge, 1983). Discrimination tasks rely on attention more than detection tasks do (e.g., Bashinski & Bacharach, 1980; Bonnel & Miller, 1994). This difference may be due to the fact that detection requires the visual system to solve a simpler problem than discrimination (e.g. Egeth, 1977; Eriksen & St. James, 1986; Jonides, 1981; LaBerge, 1983; LaBerge & Brown, 1986; Carrasco, 2011). Thus, according to some authors, whereas a simple detection task is not suitable for studying the effects of the focal component because of its lack of sensitivity to the degree of concentration of attentional resources, a discrimination task would be best-suited because it requires more attentional resources (e.g. Egeth, 1977; Eriksen & St. James, 1986; Jonides, 1981; LaBerge, 1983; LaBerge & Brown, 1986). On the other side, some authors (e.g. Posner, 1980, Benso et al., 1998; Castiello & Umiltà, 1990; Facoetti, Paganoni, Turatto, Marzola & Mascetti, 2000) have argued that the use of recognition or discrimination tasks is not really optimal to study the processing of focusing attention, given that, in addition to visual attention, other processes like expectation (categorization of the stimulus) and intention (selection of the correct response) are involved during these tasks (e.g. Van der Heijden, 1992; Facoetti et al., 2000). According to these authors, the use of a simple detection task is perfectly suitable for studying both the orienting and focusing of attention. Thus, to date, it has yet to be clarified whether task demands have an effect on the deployment of the focal component, or if the characteristics and the temporal dynamics of this component can be disclosed both by detection and discrimination tasks. Furthermore, while some studies (e.g. Bergen & Julesz, 1983; Nagy & Sanchez, 1990; Pashler, 1987) have suggested that the attentional effect in visual search tasks can depend on the stimuli used, other studies (e.g. Verghese & Nakayama, 1994; Palmer, Ames & Lindsey, 1993) have found that the attentional effect is independent of the stimulus. However, the effect of the stimulus used has not been investigated directly in the domain of focal attention and a clear answer to this question cannot yet be given.

To this aim, we performed a series of experiments to compare the effects of the task demand and of the stimulus used on the focal component and on its temporal characteristics. In particular, we carried out four different experiments in which the task and the target stimulus were, respectively: shape detection (Experiment 1a), shape discrimination (Experiment 1b), letter detection (Experiment 1c) and letter discrimination (Experiment 1d). The shape detection task and the shape discrimination task were chosen because of their wide use in the literature (e.g. Benso et al., 1998; Maringelli & Umiltà, 1998; Turatto et al., 2000; Usai et al., 1995). By contrast, the letter detection and the letter discrimination tasks were selected in order to investigate the effect of the focal component on letter identification and, more generally, on reading. Indeed, previous studies have demonstrated that attention may play an important role in normal reading behaviour (e.g. Franceschini, Gori, Ruffino, Pedrolli & Facoetti, 2012; Gabrieli & Norton, 2012; Casco, Tressoldi & Dellantonio, 1998) and developmental dyslexia (Ackerman, Dykman & Gardner, 1990; August & Garfinkel, 1990; Henderson & Ferreira, 1990), however they did not distinguish between the two components of visuo-spatial attention.

In Experiment 1a the order of the cue presentation was also manipulated. Some authors have previously shown that the relationship between the efficiency of processing and the size of the attentional focus is detectable only when the cue size changes from one trial to another, suggesting that an additional strategic component can play a role when the cue sizes are fixed (Maringelli & Umiltà, 1998; Hawkins et al., 1988). Thus, in Experiment 1 the additional aim was to replicate these findings that the cue-size effect is detectable only when the cue sizes are randomized across trials.

2.2. Experiment 1a – Shape Detection

2.2.1. Materials and methods

Participants

Twenty healthy volunteers (12 females, mean age = 24.16 ± 1.38, range = 22 – 27) took part in Experiment 1a. All participants had normal or corrected-to-normal vision and all of them were right-handed. None of them had neurological, psychiatric or other relevant medical problems.

Participants were all naïve to the experimental procedure and to the purpose of the study. They gave informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The experimental paradigm used in Experiment 1a was based on the paradigm described in a study by Maringelli and Umiltà (1998). Participants were seated in front of a computer monitor (19-inch, 400 x 300 mm) with a resolution of 1280 x 1024 pixels and a refresh rate of 60 Hz. A chin and forehead rest stabilized their head position and kept the viewing distance constant at 57 cm. Stimulus presentation, timing and response recording were carried out by the E-prime Software (Psychology Software Tools, Pittsburgh, PA).

The cue stimulus consisted of an empty square of variable size (3^0 x 3^0 or 6^0 x 6^0, thickness of 0.1°), outlined in white on a black background. The target stimulus was a red dot (diameter of 0.4°). The cue stimulus was presented in the centre of the screen and the target stimulus was always shown in the centre of the cue. A response to the target stimulus was made by pressing the space-bar on the computer keyboard.

Each trial started with a blank black screen followed 1000 ms later by one of the two possible cues (we chose not to display any fixation point to avoid giving an additional or confounding cue to participants). The cue remained on the screen until the end of the trial, while the target stimulus appeared after one of these possible SOAs: 100, 500 or 700 ms. The target stimulus remained on the screen until the participant responded (or for a maximum of 2000 ms), after which the target disappeared and the next trial started (see Figure 2.1.). In 20% of trials (catch trials) no target stimulus was presented. Participants were instructed to fixate on the centre of the screen, to focus their attention inside the square, and to press the space-bar as quickly as possible in response to the target stimulus. They were also instructed to refrain from responding on catch trials.

Every participant completed 240 trials, divided into two blocks of 120 trials each: one in which the cues were presented randomly (random block) and a second one in which the order of cue presentation was fixed (fixed block). In this latter condition the order of the presentation of the cues followed an ABBA scheme in which A consisted of 30 trials with the small cue and B of 30 trials with the big cue. Half of the participants started the experiment with the former while the remaining half with the latter. Trials were also equally divided between the 100, 500 and 700 ms SOA conditions, as well as between the two conditions of the cue (for a total of 16 trials for single condition).

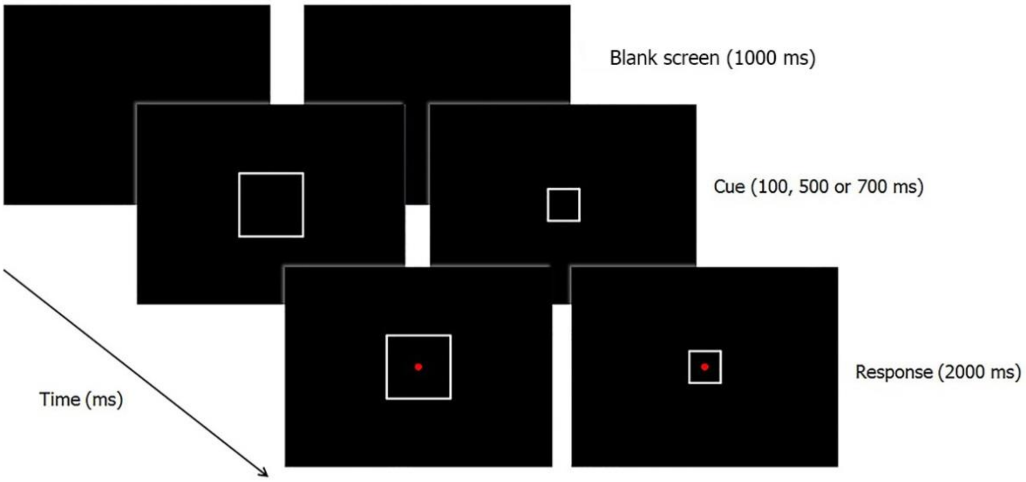

Figure 2.1. Example of a trial procedure in Experiment 1a. After a blank screen, the target appearance can be preceded by a small cue (on the right) or a big cue (on the left). After 100, 500 or 700 ms the target stimulus appeared and the participant was asked to respond as quickly as possible by pressing the space bar.

At the beginning of the experiment, a practice session composed of 10 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Statistical analyses were performed using the software IBM SPSS Statistics 22. Reaction times (RTs, measured from the onset of the target stimulus to response emission) were analysed via a two-way repeated-measures Analysis of Variance (ANOVA). Significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported). The effect size in the ANOVA was also measured by computing the Eta Squared (η2), which express the degree of association between an effect and the dependent variable, i.e. the proportion of the total variance that is attributable to a factor (Cohen, 1973). Trials with false alarms, i.e. responses to catch trials, and atypical RTs outliers (employing as a criterion 2.5 SDs above or below the mean within each participant) were discarded and not analysed. Results from the random block and the fixed block were analysed separately.

The cue-size effect was also computed in order to obtain an amodal quantification of the advantage of narrowing the focal component comparably across the four experiments. To this aim, for each participant and each SOA condition we computed the Cohen's d between the big square and the small square conditions. This measure was used because, as opposed to the simple subtraction of the mean RTs for the small cue from the mean RTs for the big cue, it also takes into account the variability in response speeds. The mean Cohen's d cue-size effect for each condition was then tested with a one-sample t-test.

2.2.2. Results

RTs were submitted to two-way repeated–measures ANOVA with *Cue* (small square and big square) and *SOA* (100 ms, 500 ms and 700 ms) as within-subject factors, separately for the fixed and random blocks. As expected, the cue type affected participants' performance only in the random condition, whereas in the fixed block condition the SOA was the only factor affecting response speed (see Figure 2.2.).

Indeed, in the fixed block condition, a significant main effect of *SOA* ($F(2,38) = 25.09$, $p < .001$, $\eta^2 = 0.362$) emerged from the ANOVA, showing that RTs were significantly slower in the 100 ms SOA condition (330 ms) compared to the 500 (300 ms) and the 700 ms (308 ms; $p < .001$ for both comparisons), which instead did not differ from each other ($p = .11$). Neither the main effect of *Cue* ($F(1, 19) = 0.945$, $p = .343$, $\eta^2 = 0.008$) nor the interaction between the two main factors ($F(2, 38) = 0.659$, $p = .523$, $\eta^2 = 0.006$) reached the statistical significance.

By contrast, in the random block condition both the main effect of *Cue* ($F(1, 19) = 16.3$, $p < .001$, $\eta^2 = 0.076$) and of the *SOA* ($F(2, 38) = 14.15$, $p < .001$, $\eta^2 = 0.281$) were significant. RTs to the target stimulus shown within the small cue (308 ms) were faster than trials in which the stimulus was shown within the large cue (318 ms). RTs in the 100 ms SOA condition (327 ms) were significantly slower compared to both the 500 ms (304 ms) and the 700 ms SOA conditions (307 ms; $p < .001$ for both comparisons), which again did not differ from each other ($p = 1.0$). The interaction between *Cue* and *SOA* was not significant ($F(2, 38) = 0.58$, $p = .56$, $\eta^2 = 0.005$), but a closer look to it showed that the difference between the small and the big cue was statistical significant in the 100 ms (322 and 331 ms, $p = .01$, respectively) and 500 ms SOA conditions (297 and 312 ms, $p = .01$, respectively). The same was not true for the 700 ms SOA condition (303 and 311 ms, $p = .09$, respectively).

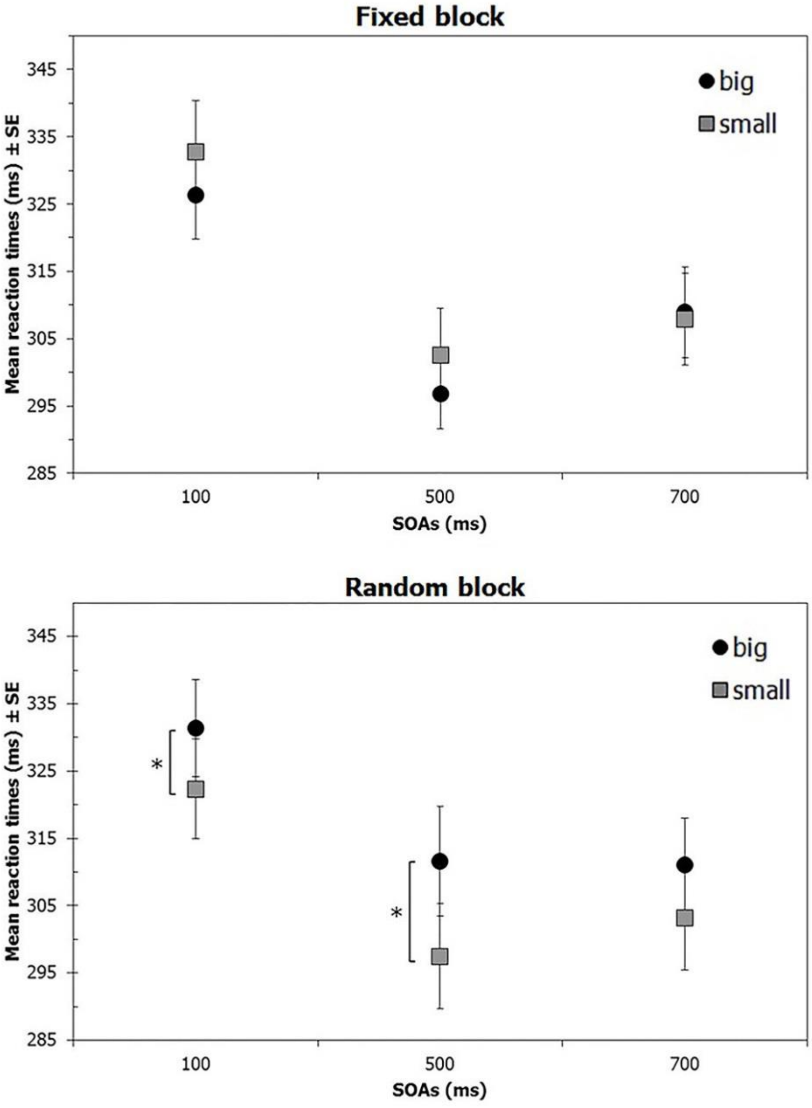

Figure 2.2. Results of Experiment 1a. Mean reaction times (RTs) in the fixed (top) and random blocks (bottom) by SOA and Cue condition. Error bars= standard error of measure (S.E.).

Regarding the catch trials, participants made very few false alarms (less than 1% in the fixed block and none in the random block), with no differences among conditions, and thus these data were not further analysed.

Results from the cue-size effect confirmed that the advantage of the small cue was present only in the random block condition. In fact in the fixed block condition the mean cue-size effect was not significantly different from zero in all the three *SOA* conditions (100 ms: -0.055, t(19) = -0.57, p = .576; 500 ms: -0.086, t(19) = -0.76, p = .455; 700 ms: -0.016, t(19) = -0.14, p = .888), whereas in the random one the cue-size effect was significantly different than zero for the 100 ms SOA (cue-size effect = 0.226, t(19) = 2.96, p = .008) and the 500 ms SOA (cue-size effect = 0.308, t(19) = 3.25, p = .004), and close to be significant in the 700 ms SOA condition (cue-size effect = 0.176, t(19) = 1.92, p = .07; see Figure 2.3).

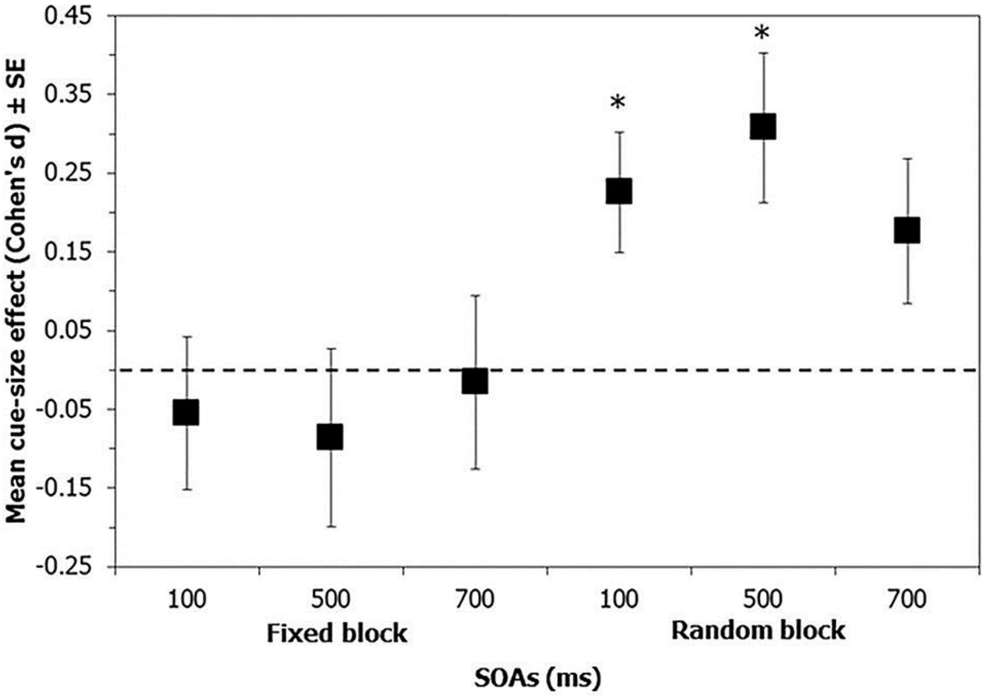

Figure 2.3. Cue-size effect for Experiment 1a for the fixed block and random block conditions. Error bars= standard error of measure (S.E.).

2.3. Experiment 1b – Shape Discrimination

2.3.1. Materials and methods

Participants

Fifteen healthy volunteers (11 females, mean age = 22.73 ± 2.66, range = 20 – 28, all right-handed) took part in Experiment 1b. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

Participants were all naïve to the experimental procedure, and to the purpose of the study and they gave informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The same general procedure of Experiment 1a was chosen for Experiment 1b, with the main difference of the task, which consisted in a shape discrimination task, instead of a detection task.

The cue stimulus consisted again of an empty square of variable size (3º x 3º or 6º x 6º, thickness of 0.1°), outlined in white on a black background, presented at the centre of the screen. The target stimuli were a red dot (diameter of 0.4°), or a red rhombus (0.4° x 0.4°). The target stimulus was always shown in the centre of the cue, and a response to the target stimulus was made by pressing one of two possible buttons on the computer keyboard.

Each trial started with a blank black screen followed 1000 ms later by one of the two possible cues. The cue remained on the screen until the end of the trial, whereas the target stimulus appeared after one of these possible SOAs: 100, 500 or 700 ms. The target stimulus remained on the screen until the participant responded (or for a maximum of 2000 ms), and after that the target disappeared and the next trial started. Participants were instructed to fixate on the centre of the screen, to focus their attention inside the square, and to press one button if the target stimulus was the red dot or another button if it was the red rhombus.

Every participant completed 192 trials, equally divided between the 100, 500 and 700 ms SOA conditions, between the two conditions of the cue and between the two target stimuli (for a total of 16 trials for single condition). SOA conditions and type of target stimulus were presented randomly. Since Experiment 1a showed that the advantage of the small cue was present only in the random block condition, in Experiment 1b the cue types were presented only randomly.

At the beginning of the experiment, a practice session composed of 10 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Statistical analyses were performed using the software IBM SPSS Statistics 22. Reaction times from correct trials (RTs, measured from the onset of the target stimulus to response emission) were analysed via a two-way repeated-measures ANOVA. Degrees of freedom were corrected using Greenhouse-Geisser correction when Mauchly's test revealed a violation in the assumption of sphericity. Significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported). The effect size in the ANOVA was also measured by computing the Eta Squared (η^2). Trials with atypical RTs outliers (employing as a criterion 2.5 SDs above or below the mean within each participant) were discarded and not analysed.

As for Experiment 1a, the cue-size effect was also computed by using, for each participant and each SOA condition, the Cohen's *d* between the big square and the small square condition. The mean Cohen's *d* cue-size effect for each condition was then tested with a one-sample t-test.

2.3.2. Results

Errors were rare (less than 2%), with no differences among conditions, and thus were not analysed. RTs were submitted to a two-way repeated–measures ANOVA with *Cue* (small square and big square) and *SOA* (100 ms, 500 ms and 700 ms) as within-subject factors.

Figure 2.4. shows the effects of the cues for every SOA condition. In line with Experiment 1a, RTs were faster when the target stimulus was preceded by the small cue and in the 500 ms SOA condition. Accordingly, the ANOVA showed that the main effect of *Cue* (F(1, 14) = 67.34, p < .001, η^2 = 0.190) and of *SOA* (F(1.22, 17.11) = 4.491, p < .05, η^2 = 0.161) was significant. RTs to the target stimulus shown within the small cue (315 ms) were faster than when the stimulus was shown within the large cue (337 ms). RTs in the 500 ms SOA condition (315 ms) were significantly faster than both the 100 ms (339 ms) and 700 ms (325 ms; p = .05 for both comparisons) SOA conditions, which, by contrast, did not differ from each other (p = .55). Results from the cue-size effect confirmed that the mean cue-size effect was significantly different from zero in all the three *SOA* conditions (100 ms: 0.379, t(14) = 5.36, p < .001; 500 ms: .440, t(14) = 7.21, p = < .001; 700 ms: 0.290, t(14) = 3.48, p = < .001).

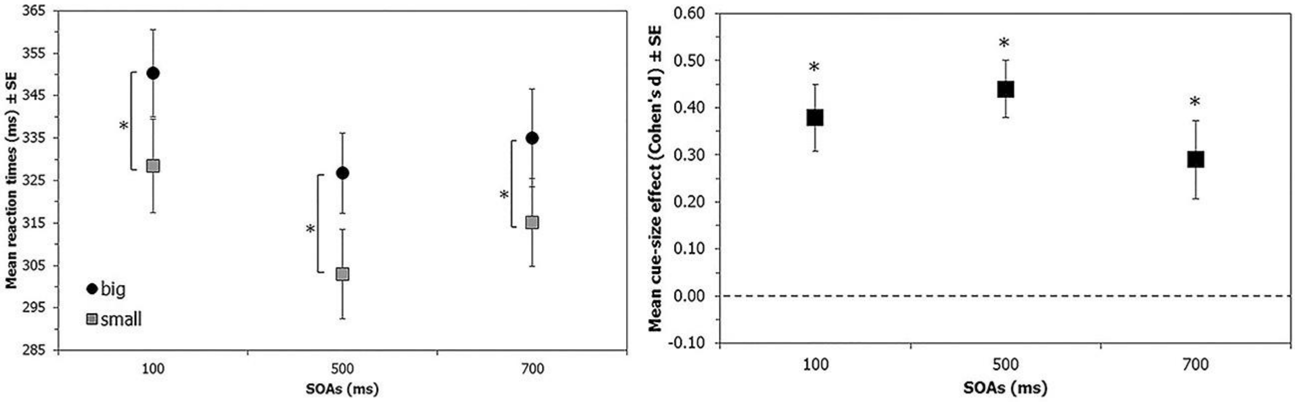

Figure 2.4. Results of Experiment 1b. Mean reaction times (RTs) by SOA and Cue conditions (left) and cue-size effect by SOA (right). Error bars= standard error of measure (S.E.M.).

2.4. Experiment 1c – Letter Detection

2.4.1. Materials and methods

Participants

Sixteen healthy volunteers (11 females, mean age = 22.70 ± 2.84, range = 20 – 28, all right-handed) took part in Experiment 1c. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

Participants were all naïve to the experimental procedure, and to the purpose of the study. They gave informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The same general procedure of Experiment 1a and Experiment 1b was used also for Experiment 1c.

The cue stimulus consisted of an empty square of variable size (3^o x 3^o or 6^o x 6^o, thickness of 0.1°), outlined in white on a black background, presented in the centre of the screen. In Experiment 1c a baseline condition in which the target appearance was not precued was also included. The target stimulus was the letter "r" (font: Courier; letter size: approximately 0.75^o x 0.75^o) and it was always shown in the centre of the cue. A response to the target stimulus was made by pressing the space-bar on the computer keyboard.

Each trial started with a blank black screen followed 1000 ms later by one of the two possible cues or by the absence of a cue. The cue remained on the screen until the end of the trial, while the target stimulus appeared after one of these possible SOAs: 100, 300, 500 or 700 ms. The target stimulus remained on the screen until the participant responded (or for a maximum of 2000 ms), after which the target disappeared and the next trial started. In 20% of trials (catch trials) no target stimulus was presented. Participants were instructed to fixate on the centre of the screen, to focus their attention inside the square, and to press the space-bar as quickly as possible in response to the target. They were also instructed to refrain from responding on catch trials.

Every participant completed 288 trials, equally divided between the 100, 300, 500 and 700 ms SOA conditions and between the three conditions of the cue (for a total of 24 trials for single condition). SOA conditions and cue types were presented randomly. At the beginning of the experiment, a practice session composed of 12 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Statistical analyses were performed using the software IBM SPSS Statistics 22. Reaction times (RTs, measured from the onset of the target stimulus to response emission) were analysed via a two-way repeated-measures ANOVA. Degrees of freedom were corrected using Greenhouse-Geisser correction when Mauchly's test revealed a violation in the assumption of sphericity, and significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported). The effect size in the ANOVA was also measured by computing the Eta Squared (η^2). Trials with false alarms, i.e. responses to catch trials, and atypical RTs outliers (employing as a criterion 2.5 SDs above or below the mean within each participant) were discarded and not analysed. For each participant, the cue-size effect was also computed as the Cohen's *d* between the big square and the small square conditions.

2.4.2. Results

Participants made very few false alarms (less than 3%), with no differences among conditions, and these data were not analysed. RTs were submitted to a two-way repeated–measures ANOVA with *Cue* (small square, big square and absence of a cue) and *SOA* (100 ms, 300 ms, 500 ms and 700 ms) as within-subject factors. The effects of the different cues on the mean RTs are shown in Figure 2.5.

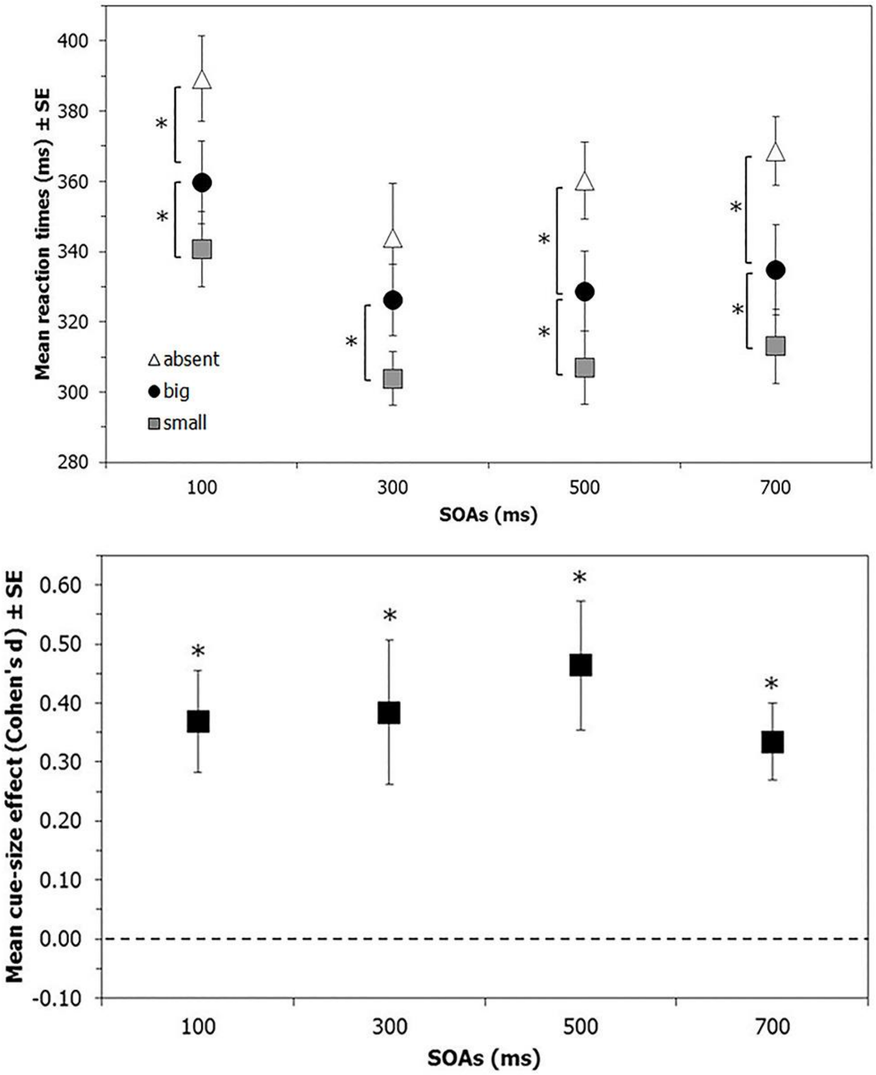

Figure 2.5. Results of Experiment 1c. Mean reaction times (RTs) by SOA and Cue conditions (top) and cue-size effect by SOA (bottom). Error bars= standard error of measure (S.E.).

The ANOVA revealed a significant main effect of the *Cue* (F(2,30) = 36.41, p < .001, η^2 = 0.369) and of the *SOA* (F(3,45) = 29.68, p < .001, η^2 = 0.189). RTs for the 100 ms SOA (363 ms) were significantly slower than the 300 ms (325 ms), 500 ms (332 ms) or 700 ms SOAs (339 ms; all p < .01). RTs to the target stimulus shown within the big cue (337 ms) and within the small cue (316 ms) were significantly different form each other and from the absence of a cue (365 ms; all p < .05). The interaction between *Cue* and *SOA* was not significant in Experiment 1c (F(2.80, 41.93)

= 0.60, p = .61, η^2 = 0.007), showing that the benefit associated with the presence of the cue was present with all SOAs. Accordingly, the mean cue-size effect was significantly different from zero in all the possible *SOA* conditions (100 ms: 0.369, t(15) = 4.30, p < .001; 300 ms: 0.384, t(15) = 3.13, p < .01; 500 ms: 0.463, t(15) = 4.23, p = < .001; 700 ms: 0.334, t(15) = 5.12, p = < .001).

2.5. Experiment 1d – Letter Discrimination

2.5.1. Materials and methods

Participants

Thirteen healthy volunteers (11 females, mean age = 23.69 ± 3.63, range = 21 – 28; all right-handed) participated in Experiment 1d. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

Participants were all naïve to the experimental procedure and to the purpose of the study. They gave informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The same general procedure of Experiment 1a, 1b and 1c was used. The cue stimulus consisted of an empty square of variable size (3° x 3° or 6° x 6°, thickness of 0.1°), outlined in white on a black background, presented in the centre of the screen. As for Experiment 1c, a baseline condition in which the target appearance was not precued was also included. The target stimulus was the letter "r" (font: Courier; letter size: approximately 0.75° x 0.75°), or the letter "t" (font: Courier; letter size: approximately 0.75° x 0.75°), and was always shown in the centre of the cue. A response to the target stimulus was made by pressing one of two possible buttons on the computer keyboard.

Each trial started with a blank black screen followed 1000 ms later by one of the two possible cues. The cue remained on the screen until the end of the trial, whereas the target stimulus appeared after one of these possible SOAs: 100, 300, 500 or 700 ms. The target stimulus remained on the screen until the participant responded (or for a maximum of 2000 ms). After the response, the target disappeared and the next trial started. Participants were instructed to fixate on the centre of the screen, to their focus attention inside the square, and to press one button for the "r" target stimulus, or another for the "t".

Every participant completed 288 trials; SOA conditions and type of cue were presented randomly (for a total of 24 trials for single condition). At the beginning of the experiment, a practice session composed of 12 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Statistical analyses were performed using the software IBM SPSS Statistics 22. Reaction times from correct trials (RTs, measured from the onset of the target stimulus to response emission) were analysed via a two-way repeated-measures (ANOVA). Significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported) and the effect size in the ANOVA was also measured by computing the Eta Squared (η^2). Trials with atypical RTs outliers (employing as a criterion 2.5 SDs above or below the mean within each participant) were discarded and not analysed. The cue-size effect was also computed by using, for each participant and each SOA condition, the Cohen's *d* between the big square and the small square conditions.

2.5.2. Results

Errors were rare (less than 3%) and thus were not further analysed. RTs were submitted to two-way repeated–measures ANOVA with *Cue* (small square, big square and absence of a cue) and *SOA* (100 ms, 300 ms, 500 ms and 700 ms) as within-subject factors.

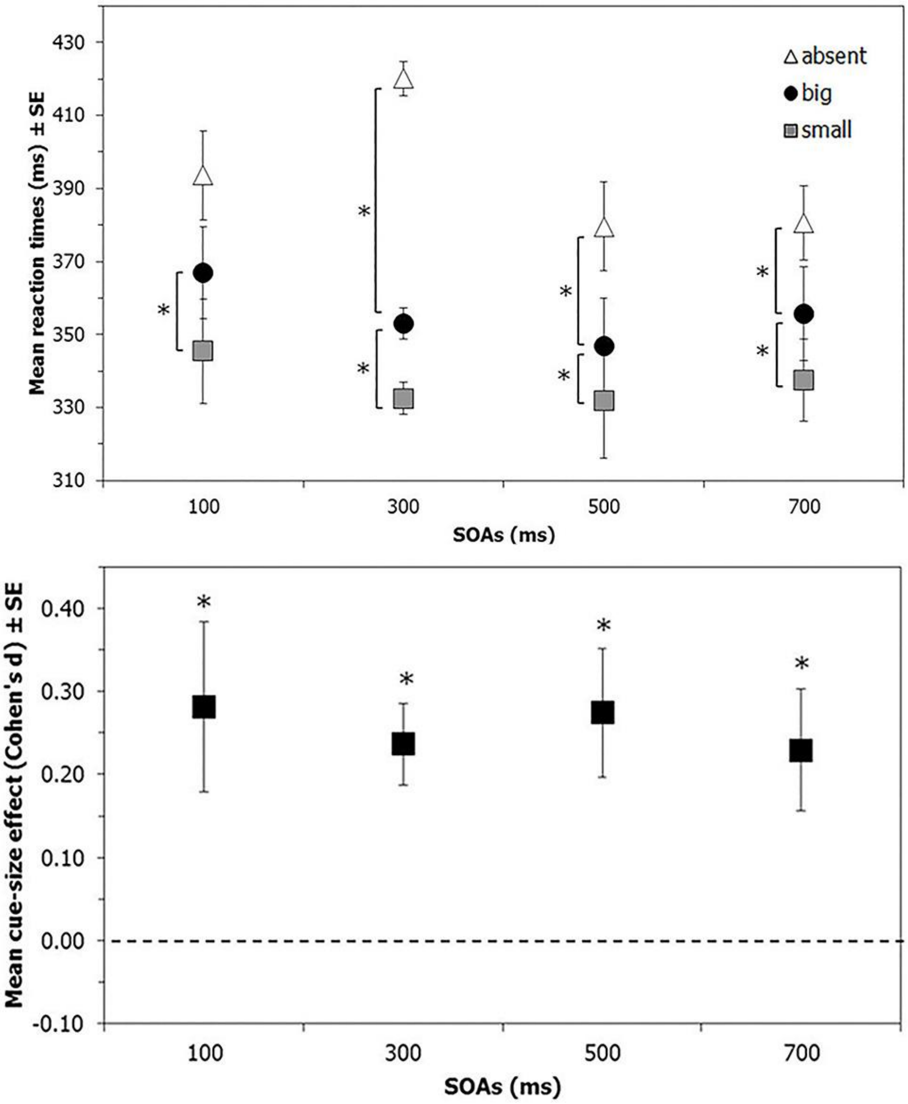

Figure 2.6. Results of Experiment 1d. Mean reaction times (RTs) by SOA and Cue conditions (top) and cue-size effect by SOA (bottom). Error bars= standard error of measure (S.E.).

The ANOVA showed that the main effect of *Cue* (F(2, 24) = 54.44, p < .001, η^2 = 0.389) was significant, whereas the main effect of *SOA* (F(3 36) = 1.29, p = .29, η^2 =0.033) was not. RTs to the target stimulus shown within the small cue (337 ms) were faster than when the stimulus was shown within the large cue (356 ms) and when any cue preceded the stimulus (393 ms; all p < .001). Participants were also faster in responding after the large cue compared to the absence of a cue (p < .001). In Experiment 1d the interaction between *SOA* and *Cue* (F(6, 72) = 4.29, p < .001, η^2 = 0.049) was also significant, showing that the small cue always elicited faster responses than the large cue and the absence of a cue, whereas the large cue evoked faster responses compared to the absence of a cue when the SOA was 300, 500 and 700 ms (see Figure 2.6.).

Results from the cue-size effect showed that the mean cue-size effect was significantly different from zero in all the possible *SOA* conditions (100 ms: 0.281, t(12) = 2.74, p < .01; 300 ms: 0.236, t(12) = 4.84, p < .001: 500 ms: 0.274, t(12) = 3.54, p = < .01; 700 ms: 0.229, t(12) = 3.10, p = < .01).

2.6. Comparing Experiment 1a, 1b, 1c and 1d

We compared the cue-size effects found in the four experiments in order to highlight the presence of any possible effects of task demands or of the stimulus used. To this aim, Cohen's d values were submitted to a three-way repeated–measures ANOVA with *SOA* (100 ms, 500 ms and 700 ms) as within-subject factor and *Task* (detection and discrimination) and *Stimulus* (shape and letter) as between-subject factors.

This analysis revealed that neither the main effect of *Stimulus* (F(1, 60) = 0.20, p = .656, η^2 = 0.0008) nor the main effect of *Task* (F(1, 60) = 0.003, p = .957, η^2 < 0.001) were significant. By contrast, the interaction between these two factors was significant (F(1, 60) = 6.87, p < .05, η^2 = 0.031), showing that the detection task was more effective when letter stimuli were used compared to shaped-stimuli (respectively 0.389 and 0.237; p < .05). The main effect of *SOA* (F(2, 120) = 1.69, p = 0.19, η^2 = 0.027) was not significant neither; however, a closer look at this effect highlighted that the cue-size effect was reduced, even if not significantly, for the 700 ms SOA (0.258) compared to the 100 ms (0.314) and 500 ms SOAs (0.371). No other effect was statistically significant.

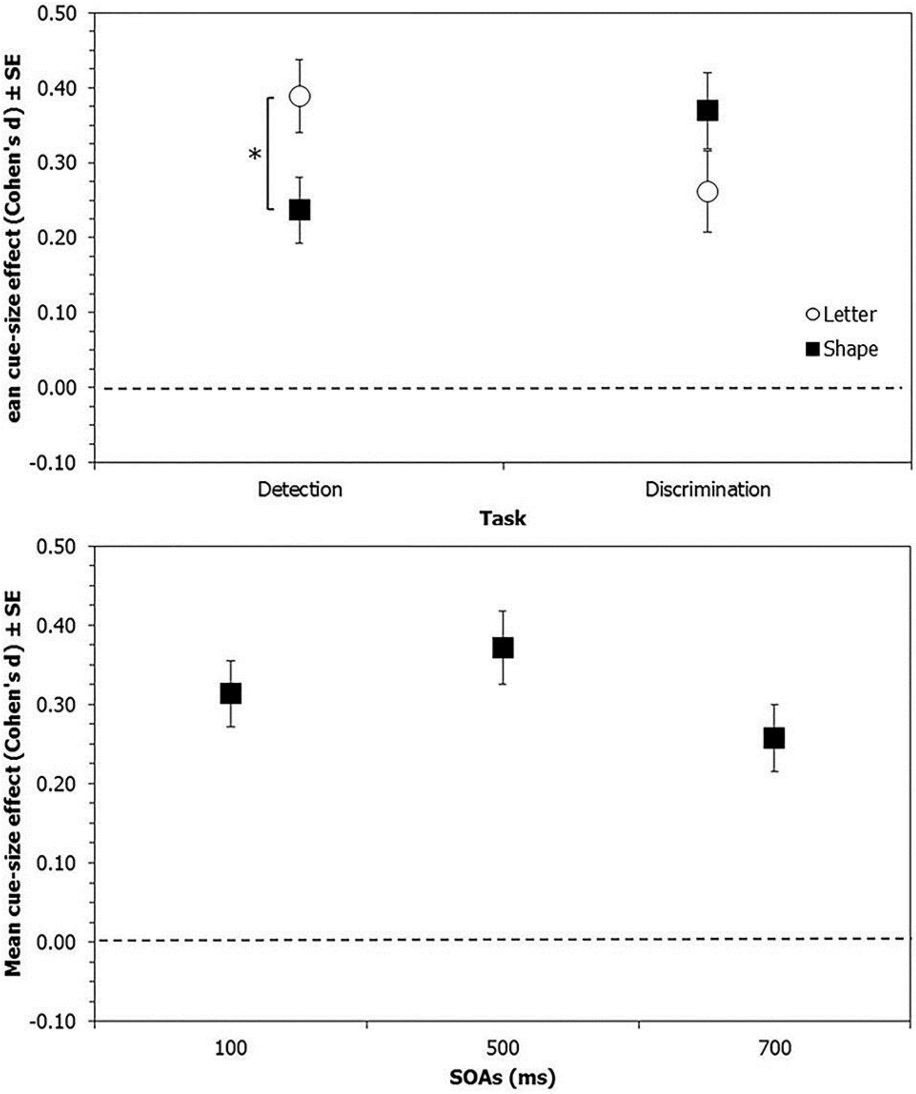

Figure 2.7. Cue-size effect by Task per Stimulus (top) and SOA (bottom). Error bars= standard error of measure (S.E.).

2.7. Discussion

The specific aim of Chapter 1 was to assess the effects of the task demand and of the type of stimulus on the focal component (i.e. the magnitude of the cue-size effect) and on its temporal trend. The results of these four experiments highlighted that the focal component of visuo-spatial attention strongly affects participants' performance in foveal vision conditions and thereby shortens their reaction times. In particular, compared to previous research on this component (e.g. Maringelli & Umiltà, 1998; Turatto et al., 2000; Usai et al., 1995), the main novel finding is that the focal component can be elicited similarly by different tasks (i.e. detection or discrimination) and different stimuli (i.e. shapes or letters).

The results of Experiment 1a (shape detection) suggested that the advantage of the focal component was more evident with short SOAs, with the best performance at 500 ms. At the longest SOA the benefit was reduced, though still detectable, probably because the effects of the inhibition of return became visible. These data are in accordance with a previous study by Maringelli and Umiltà (1998), which found that the inverse relationship between size of the attentional focus and efficiency of processing is more evident for short SOAs. Furthermore, in both studies the advantage of the small cue disappeared when the sequence of cue presentation was fixed. Taken together, the findings of both studies support the hypothesis that the characteristics of time course of the focal component are similar to the characteristics of an exogenous reaction. However, this does not imply complete independence of the focal component from endogenous control, as a cue-size effect was still detectable for the longest SOA, albeit small compared to the shorter SOA. Indeed, in Experiment 1b (shape discrimination) the benefit associated with the presence of the small cue was present also at the longest SOA, strengthening the hypothesis that though stronger in exogenous conditions, the focal component can also be deployed endogenously in foveal vision conditions. Furthermore, the results of Experiment 1b seemed to highlight that the advantage of the focal component is more robust in the case of a discrimination task.

Results from Experiment 1c and Experiment 1d showed that the temporal advantage associated with the focal component is also evident when letter stimuli are used, regardless of the SOA between the cue and the appearance of the target stimulus. In this latter case, the use of a detection or a discrimination task did not seem to affect the magnitude of the cue-size effect. Moreover, Experiments 1c and 1d showed that a greater temporal advantage was gained when the target stimulus was preceded by the big cue compared to when the target stimulus was not cued. However, more than simply reflecting the influence of the focal component, this advantage can be interpreted as a response to the temporal cue on the future appearance of the target stimulus, thereby acting as a general alert for future events in the trials. Indeed, this effect was considerably smaller than the advantage associated with the presence of the small cue, and its weakness is also supported by the fact that it was not detectable in all SOA conditions.

Finally, a direct comparison of the cue-size effects across the four experiments showed that neither the task demands nor the stimulus shape influenced the effect of the focal component substantially. However, an interaction between these two factors was found, highlighting that the effect of the focal component is more noticeable when letter stimuli are used in the case of a detection task. These results may explain the different findings in the literature, with some authors claiming that a detection task should be used (Posner, 1980, Benso et al., 1998; Castiello & Umiltà, 1990; Facoetti et al., 2000) and others that the use of a discrimination task would be more suitable (Egeth, 1977; Eriksen & St. James, 1986; Jonides, 1981; LaBerge, 1983; LaBerge & Brown, 1986). Some studies suggest that the attentional effects are dependent on the stimuli used (Bergen & Julesz, 1983; Nagy & Sanchez, 1990; Pahsler, 1987) while other studies assert that they are not (Verghese & Nakayama, 1994; Palmer et al., 1993).

Moreover, the analysis of the cue-size effect across the four experiments showed that, although the effect of the focal component was visible in all SOA conditions (i.e. 100, 500 and 700 ms), it was stronger when the SOA between the cue and the target stimulus was short. Thus, even if the temporal trend of the focal component of visuo-spatial attention includes both a primary period during which the focus is exogenously controlled (e.g. Maringelli & Umiltà. 1998; Turatto et al., 2000), and a secondary period in which the focus is endogenously maintained (e.g. Benso et al., 1998; Turatto et al., 2000), the present data support the idea that the deployment of the focal component in foveal vision is best revealed and more effective in exogenous conditions.

Chapter 3 – Dissociation between the focal and the orientation components in central and peripheral vision

3.1. Aim of the study

In the previous chapters, the effects of the focal component of spatial attention in central vision have been documented through an overview of the literature and a series of experiments. In particular, though the evidence from the literature showed that the temporal trend of the focal component includes both exogenous and endogenous periods (e.g. Maringelli & Umiltà, 1998; Turatto et al., 2000; Benso et al., 1998), the results from Chapter 2 demonstrate that the effects of the focal component in foveal vision are more evident and stronger under exogenous conditions.

However, as stated in Chapter 1, spatial attention can be allocated through both the focal component, by concentrating our resources on a limited area, and through the orientation component, by shifting attentional resources to a relevant location in the space around us (e.g. Posner, 1980; Chun et al., 2011). Nevertheless, the relationship between these two components has not yet been clarified. It is still unclear whether these two components are due to different and independent mechanisms, if they are different features of the same attentional mechanism, or if the focusing process is simply one part of the orienting process.

Previous studies have hypothesized (e.g. Castiello & Umiltà, 1990; Stoffer, 1991) or provided only indirect evidence (e.g. Turatto et al., 2000; Benso et al., 1995) that the focusing and the orienting processes are distinct processes. Indeed, these studies typically investigated the focal or the orientation components in isolation: in this way they often inferred the role of the second component from the deployment of the first one and, as a consequence, they likely confounded them. More importantly, none of these studies compared the orientation and the focal components directly, nor did they investigate how these two components work in different spatial conditions. In fact, even though attention can be captured by events located both centrally and peripherally, most studies of the orientation component used only peripheral cues to direct attention to specific locations (see Carrasco, 2011 for a review of the effects of the covert attention). Most studies of the focal component however investigated it exclusively in the centre of the visual field (e.g. Maringelli & Umiltà, 1998). Thus, even if it was suggested that the effect of spatial attention can be modulated by the eccentricity at which the attention has been allocated (Carrasco & Yeshurun, 2009), the effect of the orientation component in the centre of the visual field and the effect of the focal component in the periphery have not been examined properly so far. Finally, as suggested in Chapter 2, the particular tasks and stimuli selected to investigate the characteristics of the focal and orientation components may also affect the results and explain the differences across studies, increasing the confusion in disentangling the effects of the two components.

To sum up, nowadays we are still far from a complete characterization of the focal and the orientation components, as well as of their relationship. For this reason in the present chapter I describe two experiments aimed at obtaining evidence that focusing and orienting attention are independent processes. Here I disentangle the orientation and focal components of spatial attention by directly comparing their effects in different vision conditions (central and peripheral vision) as a function of time (short and long SOAs) and task demands (detection and discrimination). On the basis of the existing literature, we selected different cue types to elicit the focal and the orientation components of spatial attention differentially (e.g. Castiello & Umiltà, 1990; Maringelli & Umiltà, 1998; Posner, 1980): 1) a red dot, as an optimal cue for the orientation component, because it directs attention to the target location without conveying any information about the size of the target stimulus; 2) a small square, as an optimal cue for the focal component, given that it encloses the target stimulus without masking it, and it conveys information about the optimal field of integration to detect or to discriminate the target stimulus; 3) a big square, as a non-optimal cue for the focal component, because it induces focus on an area bigger than the target stimulus. Finally, a baseline condition in which the target's appearance was not precued was also included.

By comparing reaction times and cue-size effects across conditions, we aimed to demonstrate that these two attentional mechanisms operate independently in different viewing conditions, with different temporal trends and different task demands.

3.2. Experiment 2a – Detection Task

3.2.1. Materials and methods

Participants

Twenty-four healthy volunteers (17 females, mean age = 24 ± 4.21, range = 19 - 29, all right-handed) participated in Experiment 2a. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

All participants were unaware of the purpose of the experiment and participation allowed the acquisition of course credits. Each participant was asked to sign an informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

Participants were seated in front of a computer monitor (27-inch, 600 x 340 mm) with a resolution of 1920 x 1080 pixels and a refresh rate of 120 Hz. A chin and forehead rest stabilized their head position and kept the viewing distance constant at 57 cm. A Microsoft video game controller was used to collect manual responses.

Participants’ eye movements were monitored by an SR Research EyeLink 1000 eye-tracker controlled by the SR Research Experiment Builder software (SR Research Ltd, Canada). Although viewing was binocular, only the right eye was tracked at a rate of 1000 Hz.

The Experiment Builder software was also used for the presentation of the stimuli. Target stimuli consisted of a capital letter T (font Sloan, colour black) of 1° x 1° degree of visual angle oriented upright. The cue could consist of a red dot (diameter of 0.4°), or a small black square (1.2° x 1.2°, thickness of 0.1°), or a big black square (15° x 15°, thickness of 0.1°), or of no cue. Both the target stimulus and the cue were displayed on a grey background.

The experiment was divided into two different sessions, each one referring to a different condition: a *central vision* session (where both the cue and the target were presented at the centre of the screen) and a *peripheral vision* session (where both the cue and the target were presented 10° to the right of the centre of the screen). Half of the participants started the experiment with the former and the other half with the latter.

The participants had to detect the presence of the T target stimulus on the screen by pressing one button on the game controller with their right index finger. The appearance of the target was preceded by one of the 3 possible cues or by the absence of a cue (baseline), and the stimulus onset asynchrony (SOA) between the cue and the target could be either 100 or 500 ms. Each condition started with a three-point calibration and before each trial a black circle (0.6°) for drift correction was presented in the centre of the screen.

Central vision condition: Each trial started with a blank grey screen followed 1000 ms later by one of the three possible cues. As for the experiments in Chapter 2, we chose not to display any fixation point to avoid giving an additional or confounding cue to participants. After the disappearance of the cue, the T target was presented and remained on the screen until participant’s response (or for a maximum of 2000 ms), after which the target disappeared and the next trial started. In this condition both the target stimuli and the cues were always presented in the centre of the screen.

Peripheral vision condition: Each trial started with a fixation point (black circle, diameter of 0.6°) in the centre of the screen, and 1000 ms later one of the three possible cues was presented. Following, the T target was presented and remained on the screen until a response was given (or for a maximum of 2000 ms). In this peripheral vision condition, both the targets and the cues always appeared 10° to the right of the fixation point (measured from fixation point to centre of the stimulus), along the horizontal meridian. The central fixation point remained on the screen for the entire duration of the trial, in order to help the participants keep their gaze on the fixation point and not to shift it on the stimuli location.

Participants' eye movements were monitored to ensure proper fixation during both sessions: in particular, trials in which the fixation was lost or fell out of the interest area of 1° around the fixation point were discarded and presented again later (i.e. trials in which the participant fixation did not fall on the real fixation point in the peripheral vision condition, or on the centre of the screen in the central vision condition). Every participant completed 336 experimental trials per session, overall divided into 7 blocks of 48 trials. During each block, in 8 trials (corresponding to the 20% of valid trials) no target stimulus was presented (catch trials). Trials were randomised across participants and equally divided between the 100 and 500 ms SOA conditions, as well as between the four conditions of the cue (for a total of 35 trials for single condition). Before each condition, a practice session composed of 20 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Reaction times (RTs, measured from the onset of the target until a response was given) were adopted as dependent measure. Trials with false alarms, i.e. responses to catch trials, and atypical RTs outliers (employing as a criterion 2.5 *SD*s above or below the mean within each participant) were discarded and not further analysed (responses to catch trials were less than 2%

in both the central and peripheral vision conditions). Mixed-effects models (Baayen, Davidson, & Bates, 2008) were employed as primary statistical tool (software IBM SPSS Statistics 20) and the effects of interest were those associated with the experimental manipulations — that is, *Cue* (dot, small square and big square), *SOA* (100 ms and 500 ms) and their mutual interactions. The condition 'absence of a cue' was not included in the analysis, since it was more a baseline than a comparable condition. Random intercepts for participants were also introduced and significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported). Since linear mixed models (LMM) were used, the effect size, i.e. the Eta Squared (η^2), was not computed because of the difficulty of interpreting the sum of squares in a LMM as in a GLM (Bates & DebRoy, 2004).

The cue-size effect was also computed in order to obtain an amodal estimation of the effect of both the focal and orientation components. To this aim, the cue-size effect for the focal component was computed as the Cohen's *d* between the big square and the small square conditions (for each participant and each SOA condition), whereas the cue-size effect for the orientation component was computed as the Cohen's *d* between the big square condition and the dot conditions (always for each participant and each SOA condition). This procedure was favoured among other possible procedures because it makes use of the same "baseline" condition to estimate the cue-size effect of the focal or orientation components.

However, it could be argued that, whereas the dot condition represents a "pure" orienting condition, the small square condition includes both the orientation and the focal components. Therefore, the optimal procedure would consist in subtracting the baseline (absence of cue) to the dot condition and the big square condition to the small square condition: in this way it could be possible to extract one "net" marker for orienting and one for focusing, respectively. However, the use of this last procedure could introduce a distortion in the estimate of the cue-size effect, because it would be calculated by using different "baseline" conditions: one, which does not give any cues about the target stimulus (the absence of a cue), and a second one that at least provides a temporal cue about the future appearance of the target stimulus (the big square), acting as a general alert of the future events during the trials. Consequently, by following this procedure RTs in the big-square baseline condition would always be faster than RTs in the absence-of-cue baseline condition, and this would result in a bias toward the orientation effect, independently of the experimental manipulations.

Taking into account this issue, I decided to use the comparison between the small square and the dot conditions against the same "baseline" condition, because this procedure allowed us to exclude any bias due to external factors and to estimate the correct cue-size effects, which become directly comparable between each other.

The cue-size effect for the focal and the orientation components were then submitted to a three-way repeated–measures ANOVA with *Component* (focal and orientation), *Condition* (central and peripheral vision) and *SOA* (100 ms and 500 ms) as within-subject factors; the effect-size in the ANOVA was also measured by computing the Eta Squared (η^2), and significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported). As in Chapter 2, cue-size effects for each condition were then tested with a one-sample t-test against the hypothesis that they were not significantly different from zero.

3.2.2. Results

Central vision condition

Results from LMM showed that both main factors were significant (F(1, 5001) = 687.887, p < .001 for *SOA* and F(2, 5001) = 9.202, p < .001 for *Cue*). RTs were faster for trials with SOA of 500 ms than 100 ms (respectively 326 and 374 ms). RTs were also influenced differently by the cue type (346 ms for the small square, 349 ms for the dot and 356 ms for the big square). Post-hoc comparisons showed that all the differences due to the cue type were significant (all p < .005 or less) with the exception of the dot and the small square cues (p = .64).

More importantly, the interaction between *SOA* and *Cue* was also significant (F(2, 5001) = 8.917, p < .001; see Figure 3.1. A), highlighting a different effect of the cue type at different SOA intervals. In particular, the small square produced faster RTs compared to the dot and the big square cues, but only for the shorter SOA (366 ms, 378 ms and 379 ms; p < .001, respectively); by contrast, the small square and the dot cues produced similar RTs with the longer SOA (325 ms and 319 ms; p = .128, respectively) and shorter than the big square cue (333 ms; p < .05).

Peripheral vision condition

The significant factors significant in the central vision condition were also significant in the peripheral vision condition (*SOA*: F(1, 4998) = 67.171, p < .001; *Cue*: F(2, 4998) = 8.894, p < .001; and *SOA* by *Cue*: F(2, 4998) = 4.4178, p = .015). RTs for the longer SOA were faster than for the shorter one (397 ms and 417 ms, respectively), and all RTs were influenced differently by the cue type (400 ms for the dot, 409 ms for the small square and 412 ms for the big square). Post-hoc comparisons showed that the dot cue was significantly different from all the other cue types (all differences significant at p < .005 or less) and that the small square was not significantly different from the big square (p = .349).

The interaction showed again that the effect of the cue type was different for the shorter and longer SOA intervals; in particular (see Figure 3.1. B), in the shorter SOA the dot and the small square did not produce any different RTs (411 ms and 415 ms; p = .331, respectively), but they were significantly faster compared to the big square (426 ms; all differences significant at p < .01). In the case of the longer SOA, by contrast, the dot (390 ms) produced faster RTs than the small square (404 ms) and the big square (398 ms; all differences significant at p < .05 or less), whereas the small square produced RTs similar to the big square (p = .172).

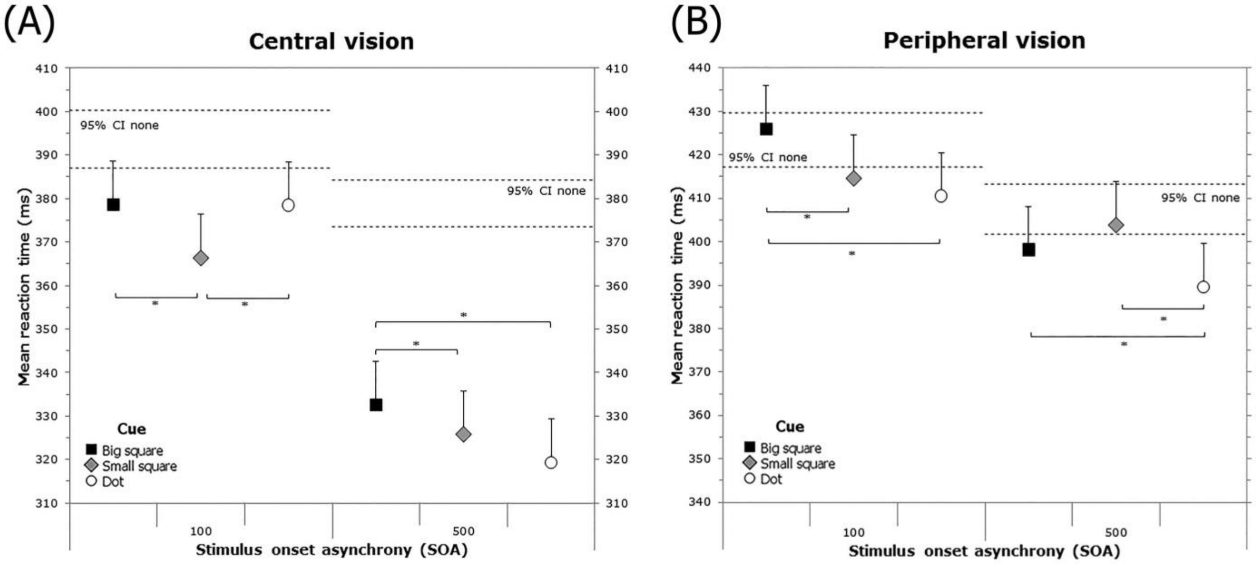

Figure 3.1. Results of Experiment 2a. Mean reaction times (RTs) in the central vision (A) and peripheral vision conditions (B) by SOA and Cue condition. Error bars= standard error of measure (S.E.).

Cue-size effects

The ANOVA showed a significant interaction between *Condition* and *Component* (F(1, 23) = 4.73, $p < .05$, $\eta^2 = 0.013$), a significant interaction between *Condition* and *SOA* (F(1, 23) = 4.43, $p < .05$, $\eta^2 = 0.028$), and a significant interaction between *Component* and *SOA* (F(1, 23) = 24.31, $p < .001$, $\eta^2 = 0.044$). Post-hoc comparisons indicated that in the periphery of the visual field the cue-size effect associated with the orientation component was significantly larger than the cue-size effect associated with the focal one (respectively 0.158 and 0.023; p = .01), and that the cue-size effect of the orientation component was larger than the focal one when the SOA between the cue and the target stimulus was 500 ms (respectively 0.209 and 0.009; $p < .001$). On the contrary, the cue-size effect of the focal component was larger for the 100 ms SOA compared to the 500 ms SOA (0.165 and 0.009; p = .008, respectively).

Lastly, we tested the mean cue-size effect of both the focal and orientation component at each condition against the hypothesis that they did not significantly differ from zero. Again, the cue-size effect associated with the focal component was significantly different from zero only for the 100 ms SOA, both in central vision condition (t(23) = 3.27, $p < .005$) and in peripheral vision condition (t(23) = 2.16, p = .042), whereas the cue-size effect of the orientation component was significantly detectable for the 500 ms SOA in central vision condition (t(23) = 3.56, p < .005) and, more interestingly, in the peripheral vision condition for both SOAs (100 ms: t(23) = 2.45, p = .022; 500 ms: t(23) = 2.12, p = .04).

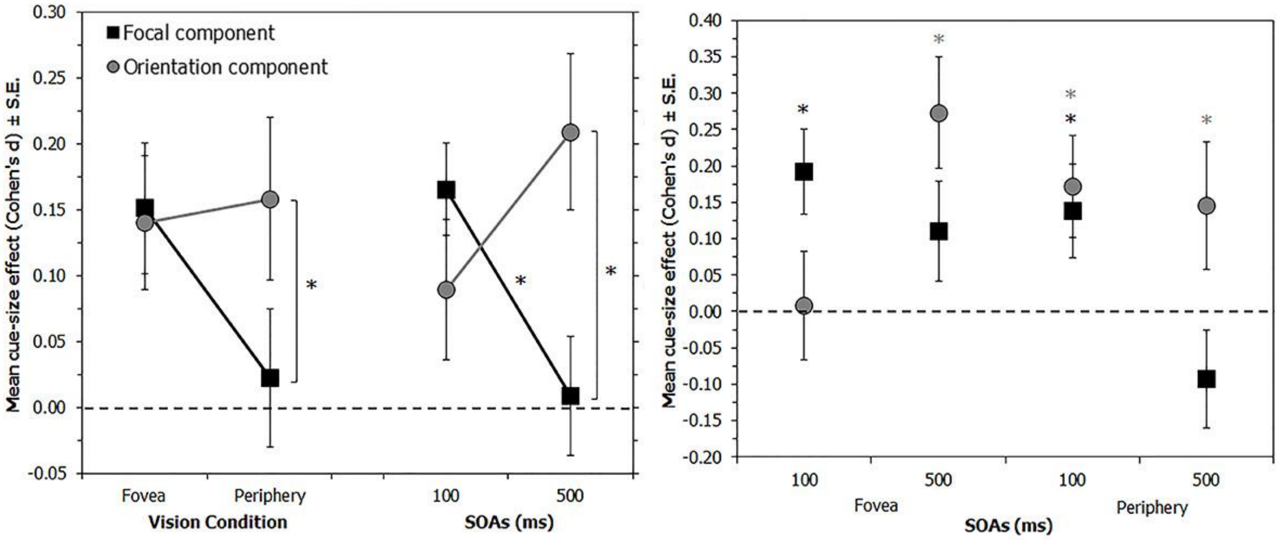

Figure 3.2. Cue-size effect for Experiment 2a shown as a function of *SOA* and *Condition* (left) and against the null-hypothesis (right). Error bars= standard error of measure (S.E.).

Therefore, the results of Experiment 2a suggested that the focal component is more evident in central vision, and especially with the shorter SOA, whereas the orientation component is more evident in peripheral vision condition and with the longer SOA. Nevertheless, to ensure that the results of Experiment 2a were not due to the specific task used (detection task), a further discrimination task has been carried out (Experiment 2b). Particularly, the aim of Experiment 2b was to further investigate the temporal trends of the focal and orientation components, and their interaction with eccentricity, in a more demanding task, in order to explore the existence of additional dissociation between the two components.

3.3. Experiment 2b –Discrimination Task

3.3.1. Materials and methods

Participants

Twenty-eight healthy volunteers (17 females, mean age = 23.7 ± 3.37; range = 19 – 29, all right-handed) participated in Experiment 2b. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

Apparatus, stimuli and procedure

The experimental apparatus, procedure and stimuli were the same as in Experiment 2a, with the following exceptions. The target stimuli consisted of a capital letter T (font Sloan, colour black, 1° x 1° degree of visual angle) and it could appear upright or rotated by 180°. Participants were required to discriminate the orientation of the T target stimulus by pressing one button on a joystick if it was upright, or another if it was inverted. No catch trials were presented in Experiment 2b.

Statistical analysis

RTs from correct trials only (measured from the onset of the target until a response was given) were adopted as dependent measure for each session and atypical outliers (employing as a criterion 2.5 *SD*s above or lower the mean) were discarded and not further analysed (participants made very few errors, i.e. less than 1.6% in the central vision condition and less than 2% in the peripheral vision condition). Mixed-effects models (Baayen et al., 2008) were employed as primary statistical tool (software IBM SPSS Statistics 20). The effects of interest were those associated with the experimental manipulations — that is, *Cue* (dot, small square and big square), *SOA* (100 ms and 500 ms) and their mutual interactions. Random intercepts for participants were also introduced, and significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported).

As for Experiment 2a, for each participant and each SOA condition, the cue-size effect for the focal component was computed by using the Cohen's *d* between the big square and the small square conditions, whereas the cue-size effect for the orientation component was computed as the Cohen's *d* between the big square and the dot conditions. The mean Cohen's *d* cue-size effects for each component were then submitted to a three-way repeated–measures ANOVA with *Component* (focal and orientation), *Condition* (central and peripheral vision) and *SOA* (100 ms and 500 ms) as within-subject factors. Significant differences were further explored by Bonferroni post-hoc multiple comparisons (correct *p-values* are reported).

3.3.2. Results

Central vision condition

The main factors were significant (F(1, 6766) = 665.957, p < .001 for *SOA* and F(2, 6766) = 12.781, p < .001 for *Cue*). RTs were faster for trials with SOA of 500 ms than 100 ms (427 vs. 472 ms). RTs were also influenced differently by the cue type (445 ms for the small square, 449 ms for the dot and 456 ms for the big square). Post-hoc comparisons showed that all the differences associated with the cue type were significant (all p < .001) with the exception of the difference between the dot and the small square cues (p = .085).

The interaction between *SOA* and *Cue* was also significant (F(2, 6766) = 4.424, p < .01; see Figure 3.3. A) and showed a different effect of the cue type in the different SOA intervals; in particular, as in the Experiment 2a, the small square produced faster RTs than the dot and the big square cues, but only for the shorter SOA (468 ms, 475 ms, and 476 ms, respectively; p < .05). By contrast, the small square and the dot cues produced similar RTs with the longer SOA (422 ms and 423 ms, respectively; p = .761) and shorter RTs than the big square cue (436 ms; p <.001).

Peripheral vision condition

The significant factors in central vision condition were also significant in peripheral vision condition (*SOA*: F(1, 6764) = 38.705, p < .001; *Cue*: F(2, 31.127) = 31.127, p < .001; and *SOA* by *Cue*: F(2, 6.227) = 5.78, p < .005).

RTs for the longer SOA were faster than for the shorter (467 ms and 478 ms, respectively) and they were influenced differently by the cue type (463 ms for the dot, 477 ms for the small square and 478 ms for the big square). Post-hoc comparisons indicated that the dot cue was significantly different from all the other cue types (all differences significant at p < .001), whereas the small square and big square conditions did not differ from each other (p = .576). The interaction showed again that the effect of the cue type was different for the shorter and longer SOA intervals; in particular, for the shorter SOA, the dot produced shorter RTs than in any other conditions (dot: 465 ms; small square: 482 ms; big square: 488 ms; all p < .001), whereas the small square and the big square conditions did not differ from each other significantly (see Figure 3.3. B). In the case of the longer SOA, again, the dot produced faster RTs than any other cues (dot: 461 ms; small square: 472 ms; big square: 469 ms; all differences significant at p < .05 or less), whereas the small square still did not differ from the big square.

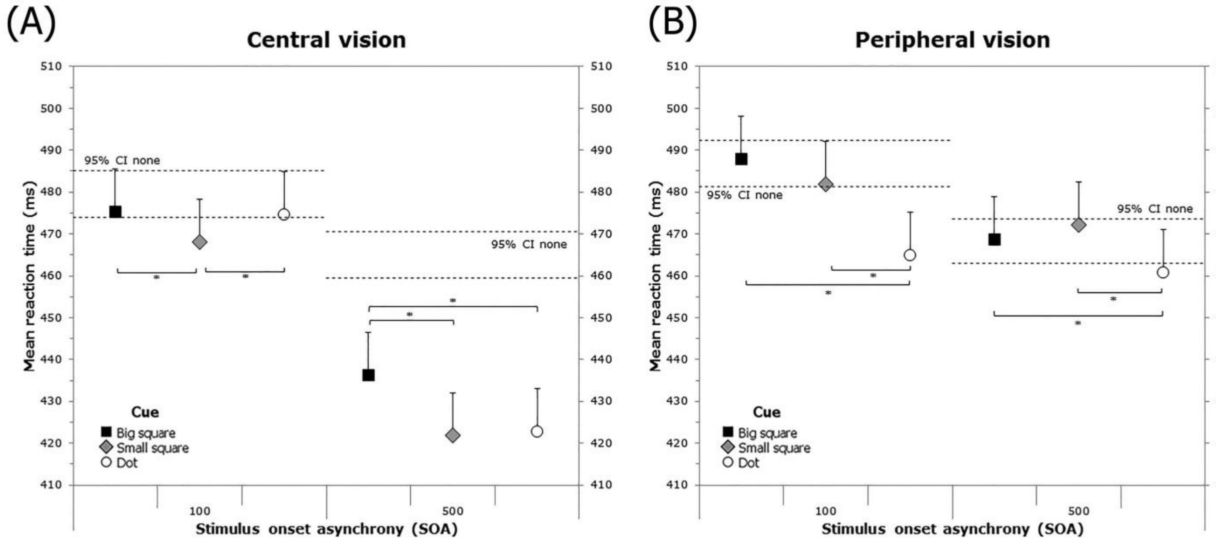

Figure 3.3. Results of Experiment 2b. Mean reaction times (RTs) in the central vision (A) and peripheral vision conditions (B) by SOA and Cue condition. Error bars= standard error of measure (S.E.).

Cue-size effects

The ANOVA highlighted a significant main effect of *Component* (F(1, 27) = 8.41, $p < .005$, $\eta^2 = 0.025$), showing that the cue-size effect associated with the orientation component (0.162) was bigger than the one associated with the focal component (0.087). However, the interaction between *Condition* and *Component* (F(1, 27) = 31.71, $p < .001$, $\eta^2 = 0.081$) and the interaction between *Condition* and *SOA* (F(1, 27) = 15.30, $p < .001$, $\eta^2 = 0.122$) were also significant. Post-hoc comparisons indicated that, compared to the focal component, the orientation component evoked a larger cue-size effect in the periphery of the visual field only (0.012 and 0.222, respectively; $p < .001$). Furthermore, the cue-size effect of the focal component was larger in the central condition compared to the peripheral one (0.162 and 0.012; $p = .008$, respectively), whereas the cue-size effect associated with the orientation component was larger in the periphery (0.222) than in the fovea (0.101; $p = .002$).

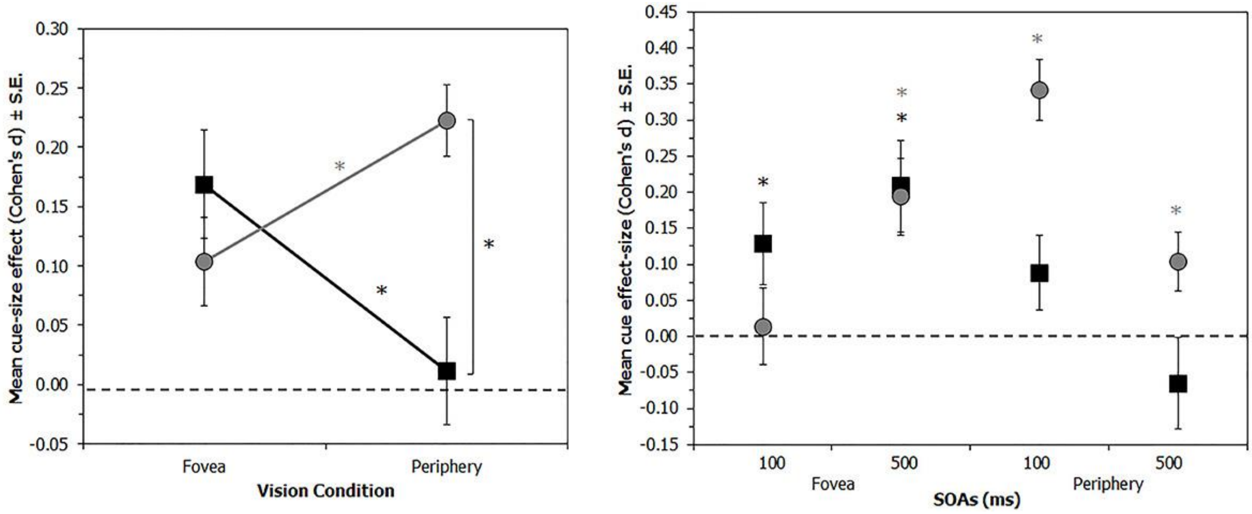

Figure 3.4. Cue-size effect for Experiment 2b shown as a function of *Condition* (left) and against the null-hypothesis (right). Error bars= standard error of measure (S.E.).

Finally, we tested again the mean cue-size effect of both the focal and orientation components of each condition against the hypothesis that they were not significantly different from zero. Supporting the results of Experiment 2a, the cue-size effect of the focal component was significantly different from zero only in central vision condition for both the 100 ms (t(27) = 2.06, p = .04) and 500 ms SOAs (t(27) = 3.27, p = .003). The cue-size effect of the orientation component differed significantly from zero in central vision at the 500 ms SOA (t(27) = 3.60, p = .001) and, more importantly, in the peripheral vision condition for both SOAs (100 ms: t(27) = 8.02, p < .001; 500 ms : t(27) = 2.54, p = .017).

3.4. Discussion

The aim of the present study was to investigate the relative influence of the orientation and focal components of spatial attention in conditions of central and peripheral vision and with different task demands (simple detection and orientation discrimination). The use of different SOAs in the experimental paradigm allowed us also to explore any further differences in the temporal trend (endogenous and exogenous) of the two components.

RTs were overall faster for the longer SOA (500 ms) than for the shorter SOA (100 ms) independent of the presence of the cue, probably because response preparation is more efficient with longer intervals. Most importantly, and consistently across tasks, the results indicated distinct RT modulation as a function of cue type, SOA and retinal location.

First of all, results from Experiments 2a and 2b confirmed that RTs are distributed differently as a function of eccentricity, i.e. detection and discrimination are faster for central targets than for peripheral targets (mean difference across conditions and experiments ranges from 13 to 79 ms). In fact, as already shown in the literature, RTs increase with eccentricity for both uncued and precued targets during detection tasks (Marzi & Di Stefano, 1981; Marzi, Mancini, Metitieri & Savazzi, 2006; Benso et al., 1998). This effect is usually attributed to changes in the distribution of covert spatial attention along the horizontal meridian of the visual field (e.g. Tassinari, Aglioti, Chelazzi, Marzi & Berlucchi, 1987).

Secondly, the interaction between SOAs, cue types and retinal eccentricity highlighted the interplay between the focal and orientation components of spatial attention. In respect to this, in Experiment 2a (detection task) we found that, in the central vision condition, the small square (i.e. the optimal cue for the focal component) was more effective than either the big square or the dot in reducing RTs, but only in the case of the shorter SOA (100 ms). For the longer SOA (500 ms), the small square and the dot were equally effective compared to the big square and the absence of a cue. On the other hand, in peripheral vision we found the opposite trend: the dot (i.e. the optimal cue for the orientation component) was more effective than either the big square or the small square in reducing RTs, but only in the longer SOA condition, whereas in the shorter SOA condition the reactions to the dot and the small square did not differ from each other (see Figure 3.1.). These results were also confirmed by the analysis of the cue-size effect associated with the focal and the orientation components. Indeed, in Experiment 2a the cue-size effect associated with the orientation component was significantly larger in the peripheral vision condition, whereas the cue-size effect of the focal component was larger for the 500 ms SOA condition in central vision (see Figure 3.2.). Similar results were replicated in Experiment 2b by using a discrimination task (see Figure 3.3. and Figure 3.4.).

According to previous studies (e.g. Carrasco, 2011: Yeshurun & Carrasco, 1999; Yeshurun & Carrasco, 1998; Carrasco & Yeshurun, 1998; Golla, Ignashchenkova, Haarmeier & Thier, 2004), covertly orienting attention to a cued location enhances spatial resolution. On the contrary, the results obtained from Experiments 2a and 2b suggest that focusing and orienting may be independently implicated in the task by appropriate experimental conditions. Indeed, taken together, these results strongly show that the effect of the focal and orientation components of spatial attention can be dissociated under constrained conditions that enable direct comparison. Focal attention does not modulate peripheral performance, but instead it dominates central vision and is exogenously triggered. The orientation component of spatial attention enhances peripheral processing time through largely, but not exclusively, endogenous control.

It could be argue that, instead of reflecting the independence of the focal and orientation components, the results obtained in Experiments 2a and 2b may be due to external factors, such as position uncertainty or perceptual saliency. According to some authors (e.g. Shaw & Shaw, 1977; Cohn, 1981), enhanced performance under cued conditions can be interpreted as the result of reduced position uncertainty rather than evidence of a pure property of attention. It should be noted that in Experiment 2a and Experiment 2b the target always appeared at the same location and thus all reported effects are netted from position uncertainty. For this reason spatial uncertainty cannot be considered as a factor that affected the results presented here.

Spatial uncertainty might affect performance differently depending on the task demand (Carrasco, 2011). Spatial cues usually convey only information that is orthogonal to the task; for instance, even if always valid in terms of location, in a discrimination task the cue can only indicate the probable target location, not any information about the correct response (e.g., the orientation of the stimulus). Therefore it is legitimate to assume that enhanced performance is due purely to the attentional effect. In the case of a detection task however, a high probability favours the observer directing their attention to a particular location, making it hard to determine if enhanced detection is due to the attentional effect or to a decision mechanism employed by the observer (Kinchla, 1992). Thus, even if a detection task would be more sensitive to the spatial uncertainty factor compared to a discrimination task, thanks to the use of a "netted" procedure we were able to observe the effects of the focal and the orientation components in both tasks. Here, the absence of invalid trials in the current paradigm and the use of both a detection and a discrimination task (unlike what was done in previous studies) is critical to the independent assessment of the focal and orientation components. Thus, although we believe that both focusing and orienting may be jointly involved in other covert attention paradigms, we demonstrated them to be independent features.

Finally, although cues were selected on the basis of their established efficacy in eliciting the focal and the orientation components of spatial attention, it could be argued that the effects we observed may be purely reflecting differences in the perceptual salience of the cues, rather than being evidence of independence between orienting and focusing mechanisms. Indeed, we compared conditions in which the target stimulus was preceded by physically different cues, i.e. a red dot and a black (small or big) square, and if colour enhances the perceptual salience of the dot we should expect faster RTs under this condition, especially in central vision where colour should be more relevant. However, our results showed the opposite trend, with faster RTs for the less salient cue (small or black square) in central vision. Furthermore, these results are in line with the expected effects based on previous studies (e.g. Maringelli & Umiltà, 1998) and they are unlikely to be due to the perceptual salience of the cue.

Hence, Chapter 3 showed that control of focus size occurs primarily in central vision, where processing capacity is the highest, supporting the hypothesis of a low attentional-focus efficiency when it is deployed outside the fovea (probably due to the poorer resolution of details in the peripheral part of the visual field). However, in the endogenous condition, participants' performance was enhanced similarly in the dot and small square conditions (i.e. the optimal cue for the spatial resolution and the optimal cue for the spatial position), whereas the exogenous condition appeared to be optimal for eliciting the focusing process. On the contrary, the optimal focal cue seemed not to affect participants' performance in the periphery of the visual field, suggesting that the focal component is absent or reduced in that area. In this condition, only the orientation cue improved participants' performance and this effect was only exogenous in the detection task, whereas it was also endogenous in the discrimination task, confirming the appropriateness of the cue used and suggesting that the control of spatial position is stronger in the periphery.

Chapter 4 – The role of the focal and orientation components in reducing the critical space and diminishing crowding in central and peripheral vision

4.1. Aim of the study

Through the experiments described so far, we demonstrated that the focal and the orientation components of spatial attention are independent of each other and due to dissociated mechanisms: the former operates primarily in central vision, where visual information processing capacity is highest, and is mainly exogenous, whereas the latter component operates mainly in the periphery of the visual field and is mainly endogenous.

The present chapter investigates the role of both components in modulating foveal and peripheral crowding. Crowding refers to the impaired recognition or identification of a target stimulus when other stimuli surround it (Stuart & Burian, 1962). This phenomenon is usually explained in terms of erroneous inclusion of features to be integrated within a spatial window, known as the integration field (Pelli, Palomares & Majaj, 2004). Typically, when we identify a target, we have to combine information from several features within the integration field; crowding occurs when the visual system operates on an improperly large integration field or when too much information falls within a proper integration field. When this happens, the integration process includes not only the target signal but also the surrounding signals, making the former no longer sufficient for identification (e.g. Pelli et al., 2004; Solomon & Morgan, 2001). Since integration fields increase in size as the target signal moves into the periphery, crowding is usually more evident in the periphery of the visual field, where the probability that the integration field includes surrounding signals is higher.

A seminal theory of crowding argues that this phenomenon depends exclusively on the distance between the target and the surrounding signals, and on its ratio to eccentricity (Pelli et al., 2004; Parkes, Lund, Angelucci, Solomon & Morgan, 2001; Solomon & Morgan, 2001). According to this theory, the size of the integration field would be reflected in the critical distance between the target and the surrounding signal that is needed to recover identification. Bouma (1970), who was the first to analyse the critical distance in crowding, stated that the critical distance is roughly half of the target viewing eccentricity, and that it is independent of the target size. By contrast, the opposite pattern characterizes ordinary masking, i.e. the independence of the eccentricity and the dependence on stimulus size (Pelli et al., 2004).

On the other side, the attention resolution theory argues that crowding reflects the limitation of the spatial resolution of attention (e.g. He et al., 1996, 1997; Intriligator & Cavanagh, 2001). According to this last theory, critical spacing, and thus the integration field, remains proportional to eccentricity, but it also reflects the finest region that attention can select, determining the extent of crowding (e.g., Chakravarthi & Cavanagh, 2007; He et al., 1996, 1997; Tripathy & Cavanagh, 2002). Indeed, targets that are spaced more finely than the attention resolution cannot be selected individually for further processing and recognition. The finest scale of attentional resolution is limited by the scale of visual resolution (i.e. the finest spacing at which visual details can still be detected), but it is often substantially coarser than this (Intrilligator & Cavanagh, 2001). This model predicts that crowding depends also on the similarity between the distractors and the target stimulus, with possible interferences occurring only when distractors and target share their defining dimension (Andriessen & Bouma, 1976; Kooi, Toet, Tripathy, & Levi, 1994; Banks & Prinzmetal, 1976); this dependency would suggest that crowding is an effect that emerges at a fairly high level (He et al., 1996, 1997).

Some studies report that directing attention to the target location reduces the critical spacing at which distractors no longer interfere with the target stimulus (e.g. Felisberti & Zanker, 2005; Huckauf & Heller, 2002; Strasburger, 2005; Van der Lubbe & Keuss, 2001; Yeshurun & Rashal, 2010; Põder, 2007), suggesting that the reduction of critical spacing may reflect the attentional effect in reducing the size of the integration field (Carrasco, 2011). Other studies have also demonstrated that both exogenous and endogenous attention can modulate spatial resolution and stimuli appearance. Indeed, it has been shown that exogenous attention increases perceived spatial frequency, perceived gap size (Landolt C task), perceived size of moving visual patterns (Gobell & Carrasco, 2005; Anton-Erxleben, Henrich & Treue, 2007) and distorts perceived shape (Carrasco, Ling & Read, 2004), whereas endogenous attention increases perceived spatial frequency (Abrams, Barbot & Carrasco, 2010) and reduces perceived line length (Tsal & Shalev, 1996).

Thus, the deployment of attention to the target location seems to affect both the critical spacing and the stimulus appearance by enhancing the spatial resolution of the attended location. This process results in an overrepresentation of the space in the attended area and in the simultaneous suppression of the space outside that area (Suzuki & Cavanagh, 1997; Intriligator & Cavanagh, 2001). Recent studies suggest that the enhanced resolution at the attended location is also reflected in brain activity. For instance, studies on macaques have indicated that attention can shift and shrink the receptive fields in areas V4, MT and LIP, providing a possible neural mechanism for the enhancement of spatial resolution that is typically reported in behavioural literature (Anton-Erxleben, Stephan, & Treue, 2009; Connor, Gallant, Preddie, & Van Essen, 1996; Connor, Preddie, Gallant, & Van Essen, 1997; Kusunoki & Goldberg, 2003; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006). Furthermore, it must be noted that similar results have been reported in humans: a recent neuroimaging study has demonstrated that attention can modulate spatial resolution by improving the signal-to-noise ratio from V1 to V4 and by narrowing the overlapping of the BOLD response at adjacent stimuli (Fischer & Whitney, 2009).

Despite the evidence reported so far, the role of attention in crowding is unclear. Indeed, some studies have found that attention reduces critical spacing only at some eccentricities (Strasburger, 2005; Van der Lubbe & Keuss, 2001), whereas others studies did not report this effect at all (e.g. Scolari, Kohnen, Barton & Awh, 2007). Further studies also failed to find an attentional effect on perceived spatial frequency (e.g. Prinzmetal, Amiri, Allen & Edwards, 1998). It should be mentioned that most of the studies on this topic investigated the crowding phenomenon and how it can be modulated by attention in only the periphery of the visual field. As mentioned before, crowding is more pronounced in peripheral vision, where the integration fields are increased in size, whereas the extent of crowding in the fovea is smaller (Fine, 2004; Pelli et al., 2004). This dissimilarity may be due to the different roles of visual acuity in the two visual conditions. In fact, the integration field in the fovea usually covers only a few minutes of arc, which is close to the acuity threshold (Latham & Whitaker, 1996), whereas the size of the integration field in the periphery is mainly independent of visual acuity and it increases according to the eccentricity (Pelli et al., 2004). Thus, given this limited extension of the integration fields in central vision, both foveal crowding and the attentional effects on it are less pronounced and harder to detect compared to peripheral crowding. Accordingly, some studies have reported that crowding is absent in fovea (e.g. Strasburger, Harvey, & Rentschler, 1991; Pelli & Tillman, 2008; Levi, 2008) and that, since it would be more limited by visual acuity, foveal crowding is less sensitive to the effect of attention compared to peripheral crowding (Flom, 1991; Leat, Li & Epp, 1999; Strasburger & Rentschel, 1995). The studies just mentioned suggested that foveal crowding might simply consist of contrast masking (Levi, Klein & Hariharan, 2002) or occur as a consequence of the physics of the stimulus (Liu & Arditi, 2000; Hess, Dakin & Kapoor, 2000). However, other studies have shown that crowding occurs in foveal vision as well (e.g. Flom, Weymouth & Kahneman, 1963; Westheimer & Hauske, 1975; Levi, Klein & Aitsebaomo, 1985; Westheimer, Shimamura & McKee, 1976; Chung, Levi & Legge, 2001; Butler & Westheimer, 1978; Lev, Yehezkel & Polat, 2014; Siderov, Waugh & Bedell, 2013) and that its extent varies from 5 arc minutes (Flom et al., 1963) to 0.5 degrees (Chung et al., 2001). Thus, whether the same mechanisms responsible for peripheral crowding are also involved in foveal crowding and whether it could be modulated by attention is still a matter of debate.

However, those differences across studies on the different effects of attention on foveal and peripheral crowding might be related to the different effects of the focal and orientation components in foveal and in peripheral vision. Indeed, as demonstrated in the previous chapters, the focal component operates primarily in central vision and is mainly exogenous, whereas the orientation component operates mainly in the periphery of the visual field. Thus, it is possible that previous studies failed to find an attentional effect on peripheral crowding, and especially on foveal crowding, because they did not take into account the specific role of each of these two components. Hence, we hypothesized that the focal component would be more effective in reducing the critical space in a condition of foveal vision, whereas the orientation component would have a stronger role in the periphery. As in Chapter 3, in this further study the focal and the orientation components were selectively elicited by using different cue types: 1) a red dot, as the optimal cue for the orientation component; 2) a small square, as the optimal cue for the focal component and 3) a big square, as the non-optimal cue for the focal component. Lastly, a baseline condition in which the target appearance was not precued was also included.

4.2. Experiment 3a – Foveal crowding

4.2.1. Materials and methods

Participants

Twenty-seven healthy volunteers (19 females, mean age = 24.9 ± 3.48, range = 20 - 33, 24 right-handed and 3 left-handed) participated in Experiment 3a. All participants had normal or corrected-to-normal vision and none of them had neurological, psychiatric or other relevant medical problems.

All participants were unaware of the purpose of the experiment and participation allowed the acquisition of course credits. Each participant was asked to sign an informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The stimuli and procedure were based on the paradigm described in a study by Toet & Levi (1992; see Figure 4.1). Participants were seated in front of a computer monitor (27-inch, 600 x 340 mm) with a resolution of 1920 x 1080 pixels and a refresh rate of 120 Hz. A chin and forehead rest stabilized their head position and kept the viewing distance constant at 300 cm. Manual responses were collected by using a computer keyboard and the dominant hand was always used.

The Experiment Builder software was used for the presentation of the stimuli. Target stimuli consisted of a capital letter T (font Sloan, colour black) of 0.05° x 0.05° degree of visual angle that could appear upright or rotated by 180°, whereas the flanker stimuli consisted of a capital letter H (font Sloan, colour black) of the same size, which could appear upright or rotated by 90°. All the stimuli had a stroke width of 1 pixel. The distance between the target and the flankers varied as a factor of the target size from 1 to 2 times the size of the target stimulus (all factors: 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8 and 2, corresponding at a spacing of 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.09, 0.1 degrees). A final condition in which the target stimulus was not flanked was also included in order to have an estimation of the participant's T-acuity in this task. The cue could consist of a red dot (diameter of 0.02°), or a small black square (0.07° x 0.07°, thickness of 1 pixel), or a big black square (0.75° x 0.75°, thickness of 2 pixels), or of no cue. Both target stimulus and cue were always displayed in the centre of the screen on a grey background.

Each trial began with a blank grey screen followed 1000 ms later by one of the three possible cues or by the absence of a cue (baseline). As for experiments in Chapter 2 and 3, we chose not to display any fixation point to avoid giving an additional or confounding cue to participants. The cue remained on the screen for 100 ms (SOA), after which a second blank grey screen appeared for 100 ms (ISI). After that, the triplet of letters was then presented for 100 ms.

Participants were required to discriminate the orientation of the T target stimulus by pressing one button on the computer keyboard if it was upright, or another one if it was inverted. Participants were free to respond at any time following stimulus presentation and were told that accuracy was critical rather than speed of response. Following participant's response the next trial started. Every participant completed 800 trials; cue types and spacing between the target and the flankers were randomised across participants.

Before the main experiment, a practice session composed of 25 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

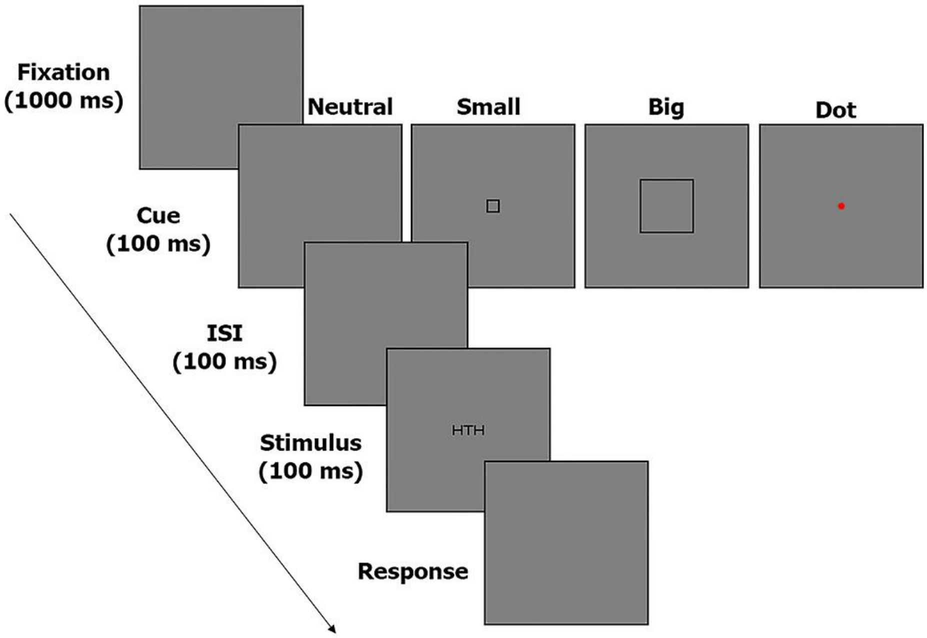

Figure 4.1. Example of a trial procedure in Experiment 3a. The size of both the stimuli and the cues shown in the figure are not the actual sizes used in the experiment, but they are adapted in order to better show the experimental procedure.

Statistical analyses

The proportion of correct responses was adopted as dependent measure and the critical manipulations were the centre-to-centre spacing between the target and the flankers and the cue types.

For each participant we first calculated the average proportion of correct responses in the T-acuity condition (absence of a cue and absence of flankers). Indeed, given the possible confusion between foveal crowding and visual acuity effects, we wanted to ensure that all stimuli were well above threshold acuity for each participant. For this reason, only the results from participants who achieved performance equal or greater than 80% in the T-acuity condition were further analysed. Consequently, sixteen out of the twenty-seven healthy volunteers initially screened were excluded (T-acuity average performance = 0.58 ± 0.13, range 0.3 – 0.75) and eleven participants (8 females, mean age = 25.2 ± 3.09, range = 21 - 31, 9 right-handed and 2 left-handed; T-acuity average performance = 0.90 ± 0.07, range 0.8 – 1.0) composed the final sample.

Accuracy data from the eleven participants were first submitted to a two-way repeated measures ANOVA with *Cue* (big square, small square, dot and absence of a cue) and *Target-Flankers Distance* (0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.09 and 0.1 degrees) as within-subject factors, excluding the trials in which the target appeared without flankers. The effect-size in the ANOVA was also measured by computing the Eta Squared (η^2), and significant differences were further explored by planned comparisons.

To determine the critical distance needed to suppress the effect of crowding, accuracy data were then analysed using the Palamedes psychometric toolbox for Matlab (Prins & Kingdom, 2009). Each observer's data at each cueing condition were fitted with a Weibull function, using a maxim-likelihood criterion. Psychometric functions were fitted by estimating the parameters α (threshold) and β (the slope) for each participant, whereas the parameters γ (the guess rate) and λ (the lapse rate) were kept fixed at 0.5 and 0.02. Initial guess of the free parameters were the same for all participants. The critical distance was defined as the target–flanker distance required for 80% of correct performance. In order to analyse differences for the resulting critical distance between cueing conditions, a one-way repeated-measures analysis of variance (ANOVA) was conducted with *Cue* (big square, small square, dot and absence of cue) as the within-subject factor. Planned contrasts were used to further investigate the difference between each cue condition and the absence of a cue, and to test the difference between the small square and the dot conditions. Effect-sizes were also measured by computing the Eta Squared (η^2). As in Chapter 3, the cue-size effects for the focal component (i.e. the difference between the big square and the small square condition) and the orientation component (i.e. the difference between the big square and the dot condition) were computed and tested against the hypothesis that they were not significantly different from zero.

Finally, accuracy and RT data were analysed using the linear ballistic accumulator, LBA (Brown & Heathcote, 2008; Donkin, Averell, Brown & Heathcote, 2009; Donkin, Brown & Heathcote, 2011). LBA is a cognitive model of decision processes that, as other cognitive models for decision (e.g. Ratcliff, 1978; Ratcliff & Rouder, 1998; Van Zandt, Colonius & Proctor, 2000), takes into account the interaction between speed and accuracy in the decision being made (Donkin et al., 2009). In particular, those models assume that, when making a decision, the observer has to sample evidence from the environment and that, as soon as the evidence reaches a threshold, the decision is made. These models have already been used to investigate the mechanisms underlying simple decision (e.g. Carpenter, 2004; Hanes & Carpenter, 1999; Reddi, 2000), recognition memory (Ratcliff, 1978), and visual discrimination (Ratcliff, 2002; Smith & Ratcliff, 2009), but they have never been applied to crowding tasks.

LBA provides estimates of three main parameters: 1) the rate at which evidence for responding accumulates (*drift rate* – with the underlying assumption that evidence accumulation occurs linearly); 2) how much evidence is required in order to give the response (*response threshold*) and 3) the amount of time taken for non-decisional aspects (*nondecision time*). Drift rates are assumed to be an indication of the stimulus quality and to be influenced by the task demand (Donkin et al., 2009). However, it has been shown that also sensory and attentional processes can modulate drift rates (e.g. Schmiedek, Oberauer, Wilhelm, Süß & Wittmann, 2007). Indeed, the size of the drift rate reflects the speed in accumulating evidence (i.e. the larger the drift rate is, the faster evidence accumulates) and its relative size describes differences in task performance between different conditions (Donkin et al., 2011).

Thus, each participant's data were fitted using the LBA (using R - http://www.R-project.org/), and drift rates for each cueing and spacing conditions were estimated. Response threshold (b), non-decision time (t_0), starting point distribution (A) and standard deviation of the drift rate (s) were fixed within each participant. In order to investigate any existing differences in the drift rate between cueing and target-flankers distance conditions, a two-way repeated-measures analysis of variance (ANOVA) was conducted, with *Cue* (big square, small square, dot and absence of a cue) and *Target-Flankers distance* (0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.09, 0.1 degrees and absence of a cue) as the within-subject factors.

4.2.2. Results

Accuracy

The first analysis on the accuracy data showed a significant effect of the *Target-Flankers Distance* (F(8,80) = 35.71, p < .001, η^2 = 0.425), demonstrating increased accuracy with increased target–flankers distance, as widely showed in many previous studies on crowding (e.g., Bouma, 1970; Pelli et al., 2004; Strasburger, 2005). The main effect of *Cue* was not significant (F(3, 30) = 2.56, p = .07, η^2 = 0.016), but a significant interaction between *Cue* and the *Target-Flankers Distance* was found (F(24, 240) = 1.58, p < .05, η^2 = 0.052), showing that the difference between the small square and the dot conditions was bigger with the smallest target-flankers distances, and that the big square increases its effect at the largest target-flankers distances (see Figure 4.2.).

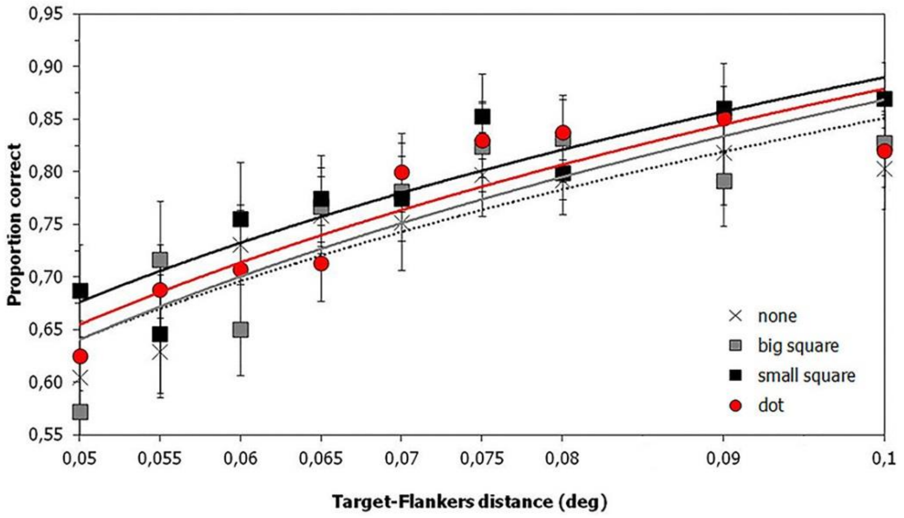

Figure 4.2. Results of Experiment 3a. Proportion of correct responses as a function of target-flankers distance and cue type. Error bars= standard error of measure (S.E.).

Critical distance

The ANOVA on the critical distance data highlighted a significant main effect of *Cue* (F(3, 30) = 4.02, $p < .05$, $\eta^2 = 0.333$; see Figure 4.3.). Planned contrasts showed that the small square decreased significantly the critical distance compared to the absence of a cue (.0709 and 0.0837 deg, respectively; F(1 ,10) = 5.24, $p < .05$), whereas neither the big square (.0859 deg; F(1,10) < 0.001, p = .643) nor the dot (.0775 deg; F(1,10) = 1.34, p = .274) were effective in reducing it. Furthermore, planned comparisons also demonstrated that the small square was significantly different from the dot condition (F(1, 10) = 7.83, $p < .05$).

As additional evidence of the differential effect of the small square and the dot, only the cue-size effect of the focal component was significantly different from zero in foveal vision (small square: t(10) = 3.10, $p < .05$; dot: t(10) = 1.66, p = 0.127; see Figure 4.3.).

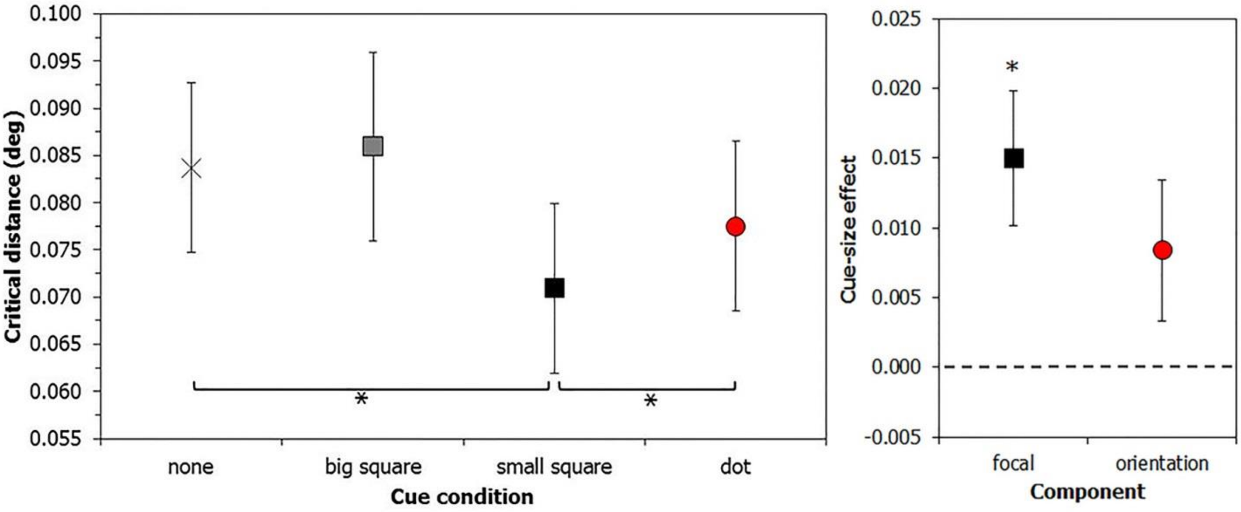

Figure 4.3. Results of Experiment 3a. Critical distance by cue type (left) and cue-size effect by component (right). Error bars= standard error of measure (S.E.).

LBA model

The ANOVA on the drift rate calculated with the LBA model showed a significant main effect of the *Cue* (F(3, 30) = 3.90, $p < .05$, $\eta^2 = 0.027$). Planned comparisons highlighted that the drift rate associated with the small square was significantly different from the one associated with the absence of a cue (0.823 and .751, respectively; F(1, 10) = 18.09, $p < .005$), whereas the drift rates of the big square (0.792; F(1, 10) = 1.60, p = 234) and the dot (0.777; F(1, 10) = 1.97, p = .191) were not; the small square condition was also significantly higher than the dot condition (F(1, 10) = 11.15, p < .01). The main effect of the *Target-Flankers distance* (F(9, 90) = 22.39, p < .001, η^2 = 0.369) was also significant, demonstrating that the drift rate increased significantly as the target–flankers distance increased.

Finally, the interaction between *Cue* and *Target-Flankers distance* was significant (F(27, 270) = 1.58, p < .05, η^2 = 0.051; see Figure 4.4.) proving that, even if the small square was always associated with the higher drift rate, the difference between the small square and the dot increased as the target–flankers distance increased.

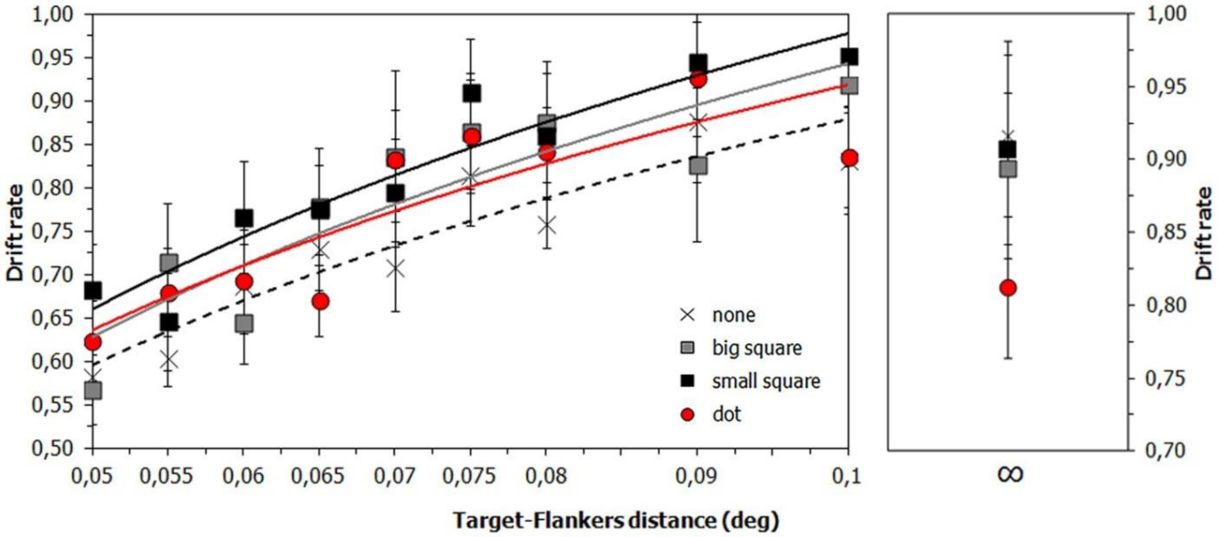

Figure 4.4. Results of Experiment 3a. Average drift rate by target-flankers distance and cue type. Error bars= standard error of measure (S.E.).

Therefore, taken together, the results of Experiment 3a suggest that the critical distance in foveal crowding can be modulated by focusing attention to the target location. Furthermore, Experiment 3a proved that foveal crowding cannot be reduced by any kinds of spatial orientation of attention: indeed, only focal attention seemed to be effective in reducing the critical distance by enhancing the processing of visual information.

4.3. Experiment 3b –Peripheral crowding

4.3.1. Materials and methods

Participants

Nine healthy volunteers (7 females, mean age = 23.3 ± 2,34, range = 19 - 26, 8 right-handed and 1 left-handed) participated in Experiment 3b. All participants had normal or corrected-to-normal vision and none of them reported neurological, psychiatric or other relevant medical problems.

All participants were unaware of the purpose of the experiment and participation allowed the acquisition of course credits. Each participant was asked to sign an informed consent prior to be enrolled in the study, which was carried out according to the guidelines of the ethical committee of the University of Milano-Bicocca, and in accordance with the ethical standards of the Declaration of Helsinki.

Apparatus, stimuli and procedure

The experimental apparatus and procedure were the same as those of Experiment 3a. Stimuli were the same used in the previous experiment, but all of them were presented 10° to the right of the fixation point (measured from fixation point to centre of the stimulus) along the horizontal meridian, and adapted for peripheral vision. In particular, stimuli size was varied in order to ensure that they were above the acuity threshold when presented at 10° of eccentricity; a further modification concerned the target-flankers distance, since, according to Bouma's law (1970), the critical distance in the periphery of the visual field is (roughly) half of the eccentricity at which the stimuli are presented.

Participants' eye movements were monitored by an SR Research EyeLink 1000 eye-tracker controlled by the SR Research Experiment Builder software (SR Research Ltd, Canada). Although viewing was binocular, only the right eye was tracked at a rate of 1000 Hz.

Target stimuli consisted of a capital letter T (font Sloan, colour black) of 0.7° x 0.7° degree of visual angle that could appear upright or rotated by 180°, whereas the flanker stimuli consisted of a capital letter H (font Sloan, colour black) of the same size, which could appear upright or rotated by 90°. All the stimuli had a stroke width of 5 pixels. The distance between the target and the flankers varied as a factor of the target size from 1 to 7.5 times the target size (all factors: 1, 1.2, 1.4, 1.7, 2.1, 2.5, 3, 3.6, 4.3, 5.2, 6.2 and 7.5, corresponding at a distance of 0.7, 0.84, 0.98, 1.19, 1.47, 1.75, 2.10, 2.52, 3.01, 3.64, 4.34 and 5.25 degrees). A final condition with a not-flanked target stimulus was also included in order to have an estimation of the participant's T-acuity in this task. The cue could consist of a red dot (diameter of 0.28°), or a small black square (0.84° x 0.84°, thickness of 2 pixels), or a big black square (10.5° x 10.5°, thickness of 5 pixels). A further condition in which the triplet was not precued was included.

On each trial, the sequence of events was the following: firstly, a blank grey screen with a central fixation point (black circle, diameter of 0.6°) was shown for 1000 ms. Then, one of the three possible cues (or the absence of a cue - baseline) was presented. The cue remained on the screen for 300 ms (SOA), after which a second blank grey screen appeared for 100 ms (ISI). After that, the triplet of letters was presented for 100 ms. Participants were asked to discriminate the orientation of the T target stimulus by pressing one button on the computer keyboard if it was upright, or another if it was inverted. The next trial started after the participant responded. The central fixation point remained on the screen for the entire duration of the trial, in order to help the participants keep their gaze on the fixation point and not to shift it on the stimuli location.

The experiment started with a three-point calibration and participant's eye movements were monitored to ensure proper fixation during the entire experimental session: in particular, trials in which the fixation was lost or fell out of the interest area of 1° around the fixation point were discarded and presented again later. Every participant completed 1040 trials; cue types and spacing between the target and the flankers were randomised across participants.

Before the main experiment, a practice session composed of 25 trials was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

As for Experiment 3a, the proportion of correct responses was adopted as dependent measure, and the critical manipulations were the centre-to-centre spacing between the target and the flankers, and the cue types.

For each participant we first calculated the average proportion of correct responses in the T-acuity condition (absence of a cue and absence of flankers), in order to ensure that the stimuli were above the acuity threshold for each of them. Only one participant performed below 80% of correct responses in the T-acuity condition (45%) and consequently his data were excluded. Eight healthy volunteers (6 females, mean age = 23.25 ± 2.37, range = 19 - 26, 7 right-handed and 1 left-handed; T-acuity average performance = 0.96 ± 0.06, range 0.85 – 1.0) composed the final sample.

Accuracy data from the final sample were first submitted to a two-way repeated measures ANOVA with *Cue* (big square, small square, dot and absence of a cue) and *Target-Flankers Distance* (of 0.7, 0.84, 0.98, 1.19, 1.47, 1.75, 2.10, 2.52, 3.01, 3.64, 4.34 and 5.25 degrees) as within-subject factors, excluding the trials in which the target appeared without flankers. The effect-size in the ANOVA was also measured by computing the Eta Squared (η^2), and significant differences were further explored by planned comparisons.

To determine the critical distance needed to suppress the effect of crowding, accuracy data were then analysed using the Palamedes psychometric toolbox for Matlab (Prins & Kingdom, 2009). Every observer's data at each cueing condition (corresponding at each cue condition within each participant) were fitted with the Weibull function, using a maxim-likelihood criterion, by estimating the parameters α (threshold) and β (the slope) for each participant, whereas the parameters γ (the guess rate) and λ (the lapse rate) were kept fixed at 0.5 and 0.02. Initial guess of the free parameters were the same for all participants. As in Experiment 3a, the critical distance was defined as the target–flanker distance required for 80% of correct performance; in order to analyze differences for the resulting critical distance between cueing conditions, a one-way repeated-measures analysis of variance (ANOVA) was conducted, with *Cue* (big square, small square, dot and absence of a cue) as the within-subject factor. Planned contrasts were used to further investigate the difference between each cue condition and the absence of a cue, and to test the difference between the small square and the dot conditions. Effect-sizes were also measured by computing the Eta Squared (η^2). The cue-size effect for the focal (as the difference between the big square and the small square conditions) and the orientation component (as the difference between the big square and the dot conditions) were computed and tested against the hypothesis that they were not significantly different from zero.

Finally, each participant's data were fitted using the LBA (using R - http://www.R-project.org/) and drift rates for each cueing and spacing conditions were estimated. Response threshold (b), non-decision time (t_0), starting point distribution (A) and standard deviation of the drift rate (s) were fixed within each participant. To explore differences in the drift rate between different cue types and different target-flankers distance, a two-way repeated-measures analysis of variance (ANOVA) was conducted, with *Cue* (big square, small square, dot and absence of a cue) and *Target-Flankers distance* (of 0.7, 0.84, 0.98, 1.19, 1.47, 1.75, 2.10, 2.52, 3.01, 3.64, 4.34, 5.25 and absence of a cue) as within-subject factors.

4.3.2. Results

Accuracy

The ANOVA on the accuracy data proved a significant effect of the *Target-Flankers Distance* ($F(11,77) = 16.58$, $p < .001$, $\eta^2 = 0.441$), showing increased accuracy with increased target–flankers distance. The main effect of *Cue* was also significant ($F(3, 21) = 6.13$, $p < .005$, $\eta^2 = 0.033$), and planned comparisons highlighted that only the overall accuracy of the dot condition (.859) was significantly higher than the accuracy of the absence of a cue (.802; $F(1, 7) = 10.83$, $p = .013$), whereas the big square (.823; $F(1,7) = 5.39$, $p = .06$) and the small square (.810; $F(1,7)$

= 0.18, p = .681) did not differ from the absence of a cue. Finally, post-hoc comparisons also demonstrated that the dot condition was significantly better than the small square (F(1,7) = 13.64, p = .008) and the big square conditions (F(1,7) = 8.47, p = .023).

The interaction between *Cue* and the *Target-Flankers Distance* was also significant (F(33, 231) = 1.49, p = .049, η^2 = 0.053), showing that the effect of the dot was more evident with the smallest target-flankers distances (see Figure 4.5.).

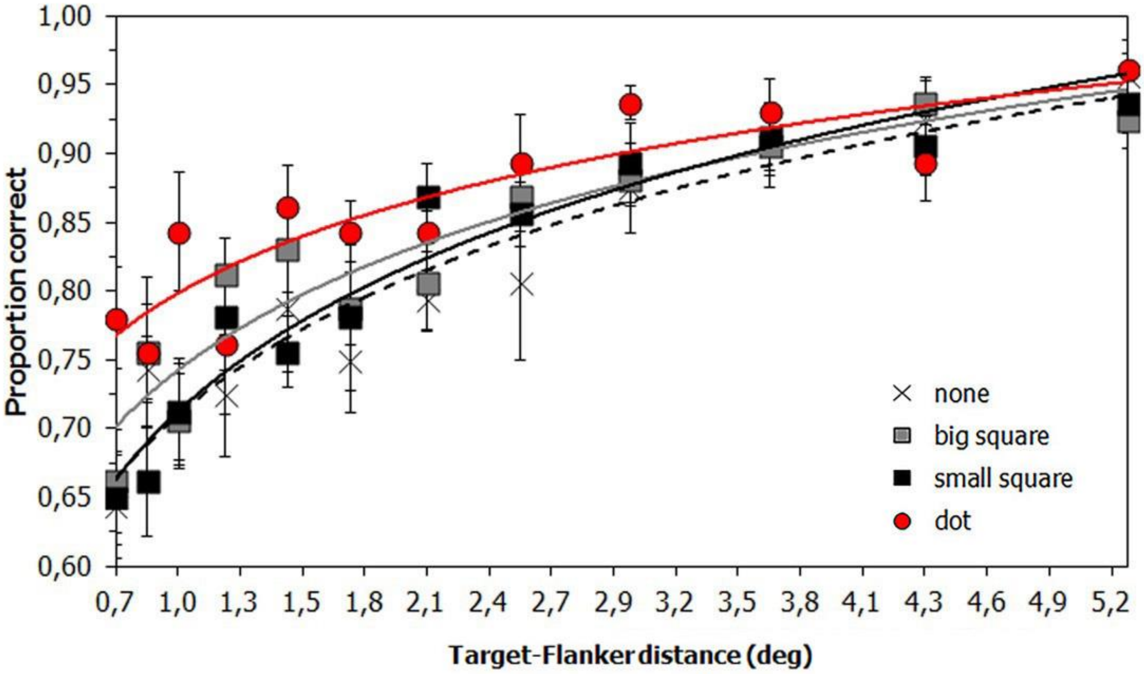

Figure 4.5. Results of Experiment 3b. Proportion of correct responses as a function of target-flankers distance and cue type. Error bars= standard error of measure (S.E.).

Critical distance

The main effect of *Cue* was significant (F(3, 21) = 4.74, p < .01, η^2 = 0.404). Planned contrasts showed that in peripheral vision only the dot significantly decreased the critical distance compared to the absence of a cue (1.04 and 1.86 deg, respectively; F(1, 7) = 9.07, p = .02), whereas neither the small square (1.72 deg; F(1, 7) = 0.23, p = .65) nor the big square (1.53 deg; F(1, 7) = 4.52, p = .07) were effective. Furthermore, planned comparisons also highlighted that the critical distance associated with the dot condition was significantly lower than the one associated with the small square (F(1, 7) = 9.37, p = .018).

As for Experiment 3a, the cue-size effect of the focal and the orientation component was tested; again, only in peripheral vision the cue-size effect of the orientation component was significantly different from zero (small square: t(7) = -0.83, p = .43; dot: t(7) = 2.64, p < 0.05; see Figure 4.6.).

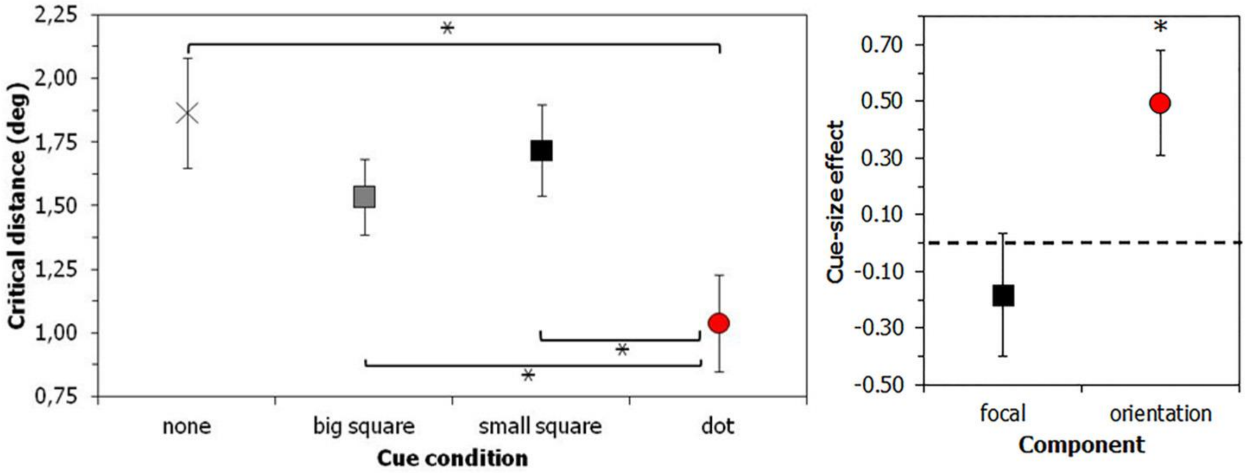

Figure 4.6. Results of Experiment 3b. Critical distance by cue type (left) and cue-size effect by component (right). Error bars= standard error of measure (S.E.).

LBA model

The main effects of *Cue* (F(3, 21) = 7.65, p < .001, η^2 = 0.038) and *Target-Flankers* distance (F(12, 84) = 18.50, p < .001, η^2 = 0.484) were significant, showing that the drift rate was modulated by the cue type and that it significantly increased as the target–flankers distance increased. In particular, planned comparisons showed that both the big square (.884; F(1,7) = 23.56, p = 0.002) and the dot (.938; F(1,7) = 20.73, p = .003) were associated with higher drift rates compared to the absence of a cue (.833), whereas the small square was not (.866; F(1,7) = 1.85, p = .216). Furthermore, the drift rate associate with the dot condition was significantly higher than both the big (F(1,7) = 5.55, p = .05) and the small square (F(1,7) = 8.45, p = .023). Finally, the interaction between *Cue* and *Target-Flankers distance* was significant (F(36, 252) =

1.50, $p < .05$, $\eta^2 = 0.046$; see Figure 4.7.), showing that, similarly to the accuracy data, the differences between cueing conditions were more evident at the smallest target-flankers distances, whereas as the target–flankers distance increased the differences between cue types tended to reduce.

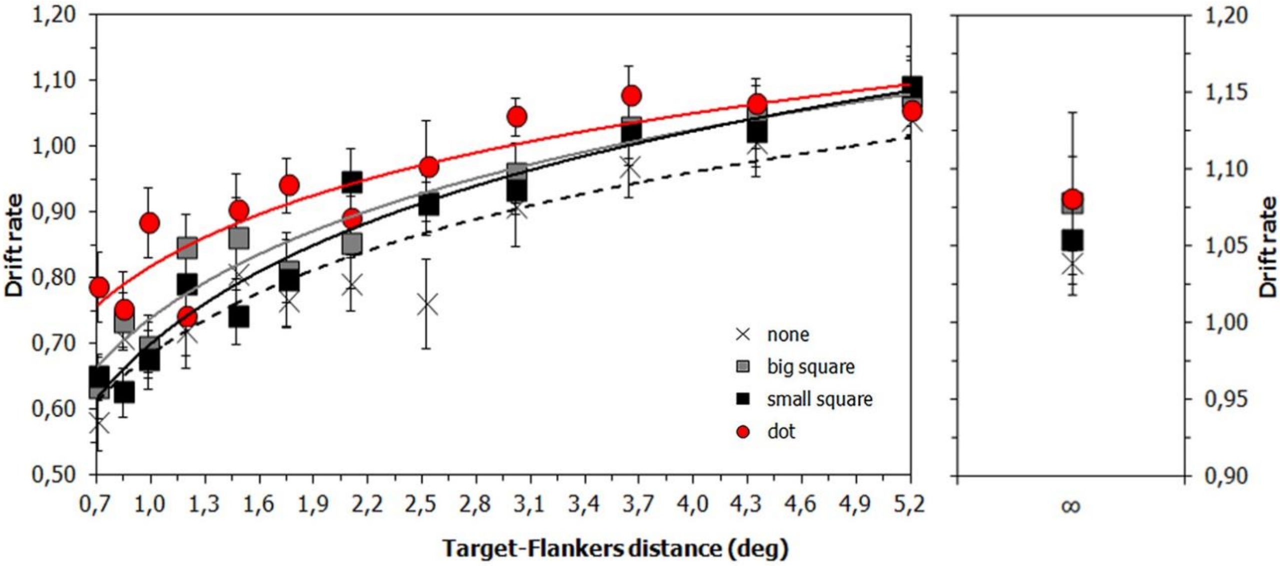

Figure 4.7. Results of Experiment 3b. Average drift rate as a function of target-flankers distance and cue type. Error bars= standard error of measure (S.E.).

Therefore, the results of Experiment 3b suggested that peripheral crowding can be reduced by directing attention to the target location. In particular, Experiment 3b demonstrated that only the orientation component of spatial attention was effective in reducing the critical distance in the periphery of the visual field, whereas the focal component did not seem to affect peripheral crowding.

4.4. Discussion

The aim of the present chapter was to investigate the different roles of the focal and orientation components in modulating crowding and reducing the critical distance in foveal and peripheral vision.

With respect to this, in Experiment 3a we found that the small square (i.e. the optimal cue for the focal component) was more effective than either the big square or the dot in reducing the critical distance in the case of central vision condition. On the other hand, in Experiment 3b we found that the dot (i.e. the optimal cue for the spatial component) was more effective than either the big square or the small square in reducing the critical distance in the case of peripheral vision. These results were also confirmed by the analyses on the cue-size effect associated with the focal and the orientation components: indeed, whereas in Experiment 3a (foveal crowding) only the cue-size effect associated with the focal component was significantly detectable, in experiment 3b (peripheral crowding) the cue-size effect of the orientation component was the only one significantly different from zero.

Previous studies have demonstrated that directing attention to the target location can reduce the critical spacing (e.g. Felisberti & Zanker, 2005; Huckauf & Heller, 2002; Strasburger, 2005; Van der Lubbe & Keuss, 2001; Yeshurun & Rashal, 2010; Põder, 2007), suggesting that attention could reduce the size of the integration fields responsible for crowding. However, our results from Experiments 3a and 3b prove that foveal and peripheral crowding are modulated independently by the two components of spatial attention, and Chapter 4 shows strongly that whereas the focal component dominates central vision, it does not modulate peripheral performance. Rather, it is the orientation component of spatial attention that enhances peripheral processing, but it does not affect foveal vision.

This dissociation could also explain the differences noticeable across previous studies on foveal crowding; indeed, as mentioned before, whereas some studies showed that crowding occurs in foveal vision (e.g. Flom et al., 1963; Westheimer & Hauske, 1975; Levi et al., 1985; Westheimer et al., 1976; Chung et al., 2001; Lev et al., 2014; Siderov et al., 2013), other studies reported that crowding is absent in fovea (e.g. Strasburger et al., 1991; Pelli & Tillman, 2008; Levi, 2008). Additionally, it has been suggested that foveal crowding could be less sensitive to the effect of attention compared to peripheral crowding (Flom, 1991; Leat et al., 1999; Strasburger & Rentschler, 1995), because of the limitation of visual acuity. However, here we demonstrated that attention can modulate both foveal and peripheral crowding: the focal component can affect the foveal one, whereas the orientation component affects only peripheral crowding. Thus, as hypothesised in the introduction of this chapter, it is possible that previous studies failed to find an attentional effect on foveal crowding because they did not take into account the independence of these focal and orientation components and the different conditions in which they operate.

Recently, it has also been shown that crowding affects the visual span (e.g. Legge, Cheung, Yu, Chung, Lee & Owens, 2007) and that the visual span predicts reading rate (e.g. Pelli, Tillman, Freeman, Su, Berger & Majaj, 2007). The visual span is the number of letters that can be processed in a glimpse, and it corresponds to the size of the uncrowded window, i.e. the letters that escape crowding (Pelli et al., 2007). The size of the uncrowded window for reading decreases as the eccentricity of the letters increases, moving away from the foveal region (Chung, Mansfield, & Legge, 1998; Legge, Mansfield, & Chung, 2001; Legge et al., 2007; Pelli et al., 2007). A recent study (Bricolo, Salvi, Martelli, Arduino & Daini, 2015) investigated the effect of crowding on normal reading by analyzing eye-movement patterns: they showed that crowding influences normal reading by increasing the first fixation duration. According to the authors, this result could be due to the role of attention, that is, longer fixations should reflect the additional involvement of attention in more difficult conditions. Consequently, a deficit in attentional processing could affect reading by increasing crowding. Some studies have demonstrated that both developmental dyslexia and reading deficits in patients with posterior cortical atrophy (PCA) are associated with pathological crowding, which causes an abnormal integration of the letters presented simultaneously (Crutch & Warrington, 2007, 2009; Atkinson, 1991; Bouma & Legein, 1977; Spinelli, De Luca, Judica, & Zoccolotti, 2002). Similarly, it has also been shown that foveal crowding is greater in the fovea of people with amblyopia (e.g. Bonneh, Sagi & Polat, 2007; Whitney & Levi, 2011) and with presbyopia (Polat, Schor, Tong, Zomet, Lev, Yehezkel et al., 2012; Polat, 2009). Some authors suggest that the anomalous crowding found in these patients could be due to an alteration of attentional mechanisms (Mendez, Shapira, & Clark, 2007; Saffran & Coslett, 1996), strengthening the hypothesis that crowding and integration fields reflect the limitation of the spatial resolution of attention. Results from Experiments 3a and 3b proved that attention can reduce crowding, suggesting that it could also affect both normal and pathological reading by modulating crowding.

Hence, experiments described in Chapter 4 showed that the size of integration fields responsible for crowding can be modulated by spatial attention. Furthermore, in accordance with the results of Chapter 3, the focal component was effective in reducing crowding only in foveal vision, where visual information processing capacity is the highest, whereas the orientation component reduced crowding only in peripheral vision, where the control of spatial position is strongest. On the basis of these results and the existing literature, we might also predict that crowding and attention could play a critical role in both normal and pathological reading, which will be the topic discussed in the following chapter.

Chapter 5 – Substitution errors in reading: neglect dyslexia or crowding dyslexia?

5.1. Aim of the study

In the previous chapter, we demonstrated that focusing and orienting can affect foveal and peripheral crowding differentially, and that attention could play a fundamental role in regulating the size of integration fields. In foveal vision in particular, focusing on a smaller visual area can increase spatial resolution and enhance the feature integration process up to the structural limit of visual acuity. It then follows that if focusing attention can reduce crowding and facilitate reading performance, one could expect an impairment in the control of attentional focus to affect reading in the opposite way by promoting enhanced crowding.

To complete this investigation, in the present study we will look for neuropsychological evidence of the existence of a causal link between focal attention, crowding, and reading errors in patients with neglect dyslexia (ND).

Neglect dyslexia is an acquired reading disorder often associated with unilateral spatial neglect (USN), and both their clinical manifestations are more frequent and severe after damage to the right hemisphere (Vallar, 2001). Neglect dyslexia affects the reading of the contralesional sides of words, sentences, and texts. USN is a neuropsychological disorder characterized by difficulty in detecting objects or executing movements in the portion of space controlateral to the lesion site, occurring even when patients are not blind to the stimulus on that side (Halligan, Fink, Marshall & Vallar, 2003; Vallar, 2001; Corbetta & Shulman, 2011). The most common anatomical correlates of USN are the right inferior parietal lobule and the temporo-parietal junction, but lesions confined to subcortical structures or involving the premotor cortex have been described as causing neglect as well (Vallar, 2001). Many different symptoms (e.g. motor and perceptual neglect, personal, peripersonal and extrapersonal neglect) and multiple cognitive impairments (e.g. spatial cognition, attention, visual awareness) can characterize each patient's specific deficit (Corbetta & Schulman, 2011). Neglect dyslexia has been proven to co-occur with USN in 40% of patients (Lee et al., 2009).

Errors in single-word reading are considered markers of ND (Ellis, Flude & Young, 1987) and they are characterized by error type. The most common errors in ND are: (i) omissions [e.g. the word "famiglia" (family) read as "miglia" (miles)] and (ii) substitutions [e.g. the word "albero" (tree) read as a nonword like "pobero"]. The relative proportion of these error types varies across patients: although omission errors predominate in the vast majority of patients (e.g. Caramazza & Hillis, 1990; Làdavas, Umiltà & Mapelli, 2007; Warrington, 1991), for some a predominance of substitution errors has been reported (e.g. Behrmann, Moscovitch, Black & Mozer, 1990; Ellis et al., 1987; Kinsbourne & Warrington, 1962). Typically, this latter type of patient produces a smaller number of errors and is more sensitive to the lexical status of the letter string (Arduino, Burani & Vallar, 2002).

In the literature, these two kinds of errors have been considered two phenomenologies of the same disorder, both depending on a single attentional mechanism that can be disrupted along a continuum of severity (see also Behrmann, Moscovitch, Black & Mozer, 1991; Mozer & Behrmann, 1990). A milder deficit would account for the substitution errors, whereas a more severe deficit would produce omission errors. However, Arduino et al. (2005), in describing RCG, a right-brain-damaged patient who manifested a spatial reading disorder characterized mostly by left-sided substitutions without any other sign of USN, suggested that substitution errors could not be directly related to the unilateral spatial disorder. Indeed, patient RCG decreased his total number of reading errors when the inter-letter spacing was increased, despite this manipulation causing the letter string to occupy a larger portion of the neglected space. According to the authors, this finding suggested that perceptual integration may play a crucial role in substitution errors (Arduino et al., 2005).

Later, Martelli et al. (2011) proposed a dual model, showing that substitution and omission errors in reading produced by neglect dyslexia patients could be due to different mechanisms: the first being a visuo-spatial mechanism responsible for omissions in both ND and USN (like left-sided errors in cancellation tasks), and the second mechanism, which causes a predominance of substitutions, being perceptual and independent from USN. Substitution errors in particular would depend on the perceptual integration process that limits letter identification, i.e. crowding: indeed, a substitution error is a visual error equivalent to a misidentification, in which the letter signal is detected but the letter identity is confused (Martelli et al., 2011). Furthermore, the similarity between the substitution errors made by patients with ND and the errors made by normal readers reading letter strings in the periphery of the visual field suggests that crowding may explain this type of error, and that increasing inter-letter spacing could reduce these errors. In line with this hypothesis, the authors found that increasing inter-letter spacing reduced substitution errors, although it increased omissions, and that omissions, but not substitutions, were related to the severity of the neglect.

Nevertheless, even though Martelli et al.'s (2011) dual model explains the mechanisms underlying the two different types of errors, it was still unclear why only some patients with USN make reading errors. An answer to this question has been addressed by a recent study by Primativo et al. (2013), who investigated the role of eye-movements in determining omission errors. Their results demonstrated that neglect patients with ND (all characterized by left-lateralized omission errors) showed abnormal eye-movement patterns in both a reading task and a non-verbal saccadic task compared to neglect patients without ND and controls. In particular, ND patients made a great number of inaccurate fixations, that is, ND patients' fixations fell outside of the stimulus both in the left and right hemispaces. Thus, Primativo et al. (2013) suggested that the omission errors of the reading disorder in ND are the phenotypic expression of the co-occurrence of the exploratory deficit of USN and of the altered oculo-motor pattern, which prevents the automatic execution of the fine eye-movements required for reading. Therefore USN patients who are compromised in visually-guided eye movement execution would be impaired also in reading, whereas those with normal eye movements would read normally (Primativo et al., 2013). According to these results and to Martelli et al.'s model (2011), the two different error types would also require specific treatments. As a consequence of the independence of the mechanisms underlying omissions and substitutions, a specific training for omission-type ND would aim to restore oculo-motor scanning but would not improve reading in substitution-type ND, whereas specific training for substitution-type ND would not improve omission-type ND.

A similar understanding of substitution errors has not yet been provided in the literature. Thus, the aim of the present chapter is to investigate the mechanisms underlying substitution errors in ND, and, more specifically, to examine the possible role of crowding, as proposed by Martelli et al.'s dual model (2011). Particularly, according to the results of the previous experiments, we might predict that an attentional deficit could play an important role in determining substitution errors in reading by enhancing crowding. Indeed, the previous chapters demonstrated that an observer's performance can be strongly modulated by deploying focal attention in foveal vision, and that letter identification can be improved when the focal component is used to shrink the integration fields. Thus, a deficit in the control of attentional focus would prevent the adjustment of the integration field on the letter to identify, resulting in an inclusion of the surrounding signals and in the consequent misidentification of the letter. Accordingly, independent of the presence of USN, patients who show impairment in the control of attentional focus would be impaired also in reading, whereas patients with spared control of focal component would read normally.

To explore this hypothesis, we tested a group of 6 patients with ND (one patient characterized by omission errors and five patients with substitution errors) in a series of experiments investigating the relationship between substitution errors and the control of focal attention, excluding alternative explanations. Particularly, the patients underwent:

(i) a reading task of pseudowords (Experiment 4a), in order to better describe and characterize the type of reading errors in the group of six patients, according to the letter position analysis used by Martelli et al. (2011).

(ii) a non-verbal saccadic task (Experiment 4b), which simulated the sequential eye-movements involved in reading, in order to assess patients' ability to execute fine eye movements, and to further confirm that substitution errors are not associated with an abnormal eye-movement pattern, which, instead, is the case of omission errors (Primativo et al., 2013; 2015);

(iii) a reading task of pseudowords (Experiment 4c) with the simultaneous eye-movement recording. The length of pseudowords and inter-letter spacing were manipulated to assess the effect of spacing on both patients' reading performance and eye-movement pattern. Indeed, previous studies demonstrated that letter recognition can be restored by increasing inter-letter spacing (e.g. Pelli et al., 2004; Whitney & Levi, 2011), and that inter-letter spacing also influences normal word reading by increasing fixations duration, suggesting a modulatory effect of attention on reading (Bricolo et al., 2015);

(iv) a reading task before and after an optokinetic stimulation, OKS (Experiment 4d) to assess the sensitivity and the specificity of omission and substitution errors to OKS. OKS was selected because (Pizzamiglio, Frasca, Guariglia, Incoccia & Antenucci, 1990) this stimulation facilitates the displacement of oculo-motor exploration toward the neglected side of space automatically, by requiring neither consciousness of the deficit nor a goal-based behaviour by the patient. In particular, we would expect OKS to be effective in reducing omission errors, since they depend on abnormal oculo-motor behaviour, but not in reducing substitution errors, which are independent of USN;

(v) a detection task (Experiment 4e) in which the appearance of the target stimulus can be preceded by cues of different sizes, in order to assess patients' ability to control and adjust attentional focus according to the task demand, in both exogenous and endogenous conditions.

5.2. Case reports

Participants

Six brain-damaged patients, showing reading difficulties at a previous screening were recruited and tested. Informed consent was obtained from all patients prior to their participation. Since omission-type ND has been extensively described in Primativo et al. (2013; 2015), here we focused our investigation on the substitution-type ND. Accordingly, five patients with prevalence of substitution errors were recruited by screening a greater population of patients over two years. For this reason, patients underwent different neuropsychological batteries, assessing the severity of their USN and their cognitive functions. Additionally, a patient with prevalence of omission errors was also recruited, in order to compare her performance to the performance of patients with substitution-type ND, and to demonstrate the independence of the mechanisms underlying omission and substitution errors.

MA, a 62-year-old female, right-handed, with 11 years of education, suffered a subarachnoid haemorrhage from a ruptured aneurysm of the right internal carotid artery in October 2012, preceded by an episode of loss of consciousness. The TC scan revealed the presence of hypodensity at the level of both the right frontal cortex and periventricular white matter (insula, supplementary motor area, middle cingulum, superior frontal gyrus, inferior frontal operculum, rolandic operculum, putamen). No occipital damage and no visual field defect were present. She showed a moderate to severe USN, whereas her language comprehension was appropriate for the demands of the present study. No evidence of visuo-perceptual deficit was observed. Finally, she had a pathological performance at a words and pseudowords reading test (Vallar et al., 1996), characterized by omission errors.

EP, a 60-year-old male, right-handed, with 13 years of education, suffered a cerebro-vascular ischemic stroke, confined to the right hemisphere. A MRI scan identified a right fronto-temporo-parietal lesion (heschl gyrus, rolandi operculum, superior fronto-occipital fasciculus, inferior frontal operculum, superior longitudinal fasciculus, superior temporal gyrus, external capsule, supramarginal gyrus, insula, superior corona radiata, putamen, middle temporal gyrus, superior temporal pole, inferior parietal gyrus). No occipital damage was present and no visual field deficit was detected. He presented a complete left hemiparesis and the neuropsychological assessment showed impulsiveness, distractibility, reduced cognitive flexibility and planning difficulties, as well as a medium to severe USN for extrapersonal and peripersonal space, and visuo-constructional and visuo-spatial skills deficits. Finally, he showed ND by means of a words and pseudowords reading test (Vallar et al., 1996), characterized by substitution errors.

NR, a 67-year-old male, right-handed, with 13 years of education, suffered a cerebro-vascular ischemic stroke, confined to the right hemisphere. A MRI scan identified a right fronto-temporo-parietal lesion, which extended also to subcortical structures. No occipital damage was present and no visual field deficit was detected. He showed a moderate to severe USN, whereas his language comprehension was appropriate for the demands of the present study. Finally, he had a pathological performance at a words and pseudowords reading test (Vallar et al., 1996), characterized by substitution errors.

RE, a 74-year-old male, right-handed, with 13 years of education, suffered an ischemic stroke confined to the right hemisphere. A TC scan identified a fronto-parietal-occipital lesion extended to the right basal ganglia. No visual field deficit was detected. He presented a complete left hemiparesis, reduced cognitive flexibility, and planning difficulties, as well as a medium to severe USN. Lastly, he showed ND characterized by substitution errors, by means of a words and pseudowords reading test (Vallar et al., 1996).

AS, a 72-year-old male, right handed, with 12 years of education, suffered a cerebellar ischemic stroke, including both the right and left hemispheres. A TC scan reported the presence of hypodensity at the level of the left cerebellum and of the right occipital cortex. His language comprehension and production were appropriate. He showed ND characterized by substitution errors, by means of a words and pseudowords reading test (Vallar et al., 1996).

CG, a 68-year-old male, right-handed, with 17 years of education, suffered an ischemic stroke confined to the left hemisphere. A TC scan showed hypodensity at the level of the insula and parieto-temporal cortex, and of the posterior periventricular white matter. No visual field deficit was detected, but the patient presented a severe aphasic impairment, which prevent him from naming common objects. Comprehension skills were appropriate. Lastly, he showed ND characterized by substitution errors, by means of a words and pseudowords reading test (Vallar et al., 1996).

Neuropsychological assessment

In order to assess the presence and severity of unilateral spatial neglect and neglect dyslexia, patients MA, EP and NR underwent a diagnostic battery, which included the following tests:

(a) *Letter cancellation* (Diller & Weinberg, 1977). The patient is asked to cross out all 104 H letters (53 on the left side and 51 on the right side). Targets are presented in alignment with other letter distractors. For healthy subjects, the maximum difference between omission errors on the two sides of the sheet is two (Vallar, Rusconi, Fontana & Musico, 1994).

(b) *Star cancellation* (Wilson, Cockburne & Halligan, 1987). The task requires crossing out all 56 small stars (27 on the left side and 27 on the right side). Targets are presented among 52 large stars, 13 letters and 10 small words. Two small stars in the centre are used for demonstration and the sheet is placed at the patient's midline. The maximum score that can be achieved on the test is 54 points (56 small stars in total minus the 2 used for demonstration). A cut-off of < 44 indicates the presence of USN (Wilson et al., 1987).

(c) *Wundt-Jastrow Area Illusion test* (Massironi, Antonucci, Pizzamiglio, Vitale, & Zoccolotti,1988). Patients are required to judge the longer of two (identical) curved shapes. The score on this test is the number of "unexpected" responses, i.e. those indicating that the patient does not show the illusory effect arising from the contralesional side of the stimulus. Typically, patients with right brain damage and left neglect make errors only on stimuli with a left-sided illusory effect.

(d) *Sentence reading* (Zoccolotti etal.,1989). Patients are required to read aloud six sentences (medium length 8.5 words, 31.8 letters; range 5–11 words, 20–41 letters) printed in upper case on an A4 sheet of paper, horizontally oriented. The final score is the number of reading errors (range 0–6). Neurologically healthy people and right-hemisphere-damaged patients without neglect make no errors in this task.

(e) *Line bisection* (Schenkenberg, Bradford & Ajax, 1980). Patients are asked to place a mark with a pencil (with their preferred or unaffected hand) through the center of a horizontal line of 16 cm of length. The final score consists of the deviation of the bisection from the true centre of the line. A deviation of more than 6 mm from the midpoint indicates USN.

(f) *Single-word reading test* (Vallar, Guariglia, Nico & Tabossi, 1996). Two out of the three stimuli sets of the original test were used: a list of 38 words and a list of 38 pseudowords. The word lists include thirty 4–9-letter words, three 10-letter words, three 11-letter words and two 12-letter words. The pseudowords were obtained from the 38 real words by changing one letter in the left half of each word, without violating the phonetic and orthographic constraints of Italian. Each stimulus was printed horizontally in black upper case letters (24-pt Geneva bold laser print) in the centre of a white sheet of paper. Participants' task was to read aloud the letter strings, while the experimenter scored responses manually. If a patient misread or omitted the left portion of the stimulus, the item was classified as a ND error using the "neglect point measure" of Ellis et al. (1987). ND errors were further categorised as omission or substitution errors: omissions consisted of all errors in which the length of the produced item was shorter than the target, whereas substitutions consisted of all errors in which the produced item had the same length as the target.

	MA	**EP**	**NR**
Gender	F	M	M
Age	62	60	67
Education	8	10	13
Lesion site	F dx	FTP dx	FTP dx
Neglect assessment			
Letter cancellation			
Left (/53)	42*	4	40*
Right (/53)	21	1	13
Star cancellation			
Left (/27)	8*	13*	21*
Right (/27)	3	5	5
Wundt-Jastrow			
Left (/20)	4*	16*	6*
Right (/20)	2	0	1
Sentence reading (/6)	6*	1*	6*
Bisection (mm)	5.4*	10.3*	14.2*
Neglect dyslexia assessment			
Words			
Errors	18/38 (47,4%)	2/38 (5.3%)	7/38 (18.4%)
Neglect errors	17/18 (94.4%)	2/2 (100%)	4/7 (57.1%)
Omissions	16/17 (94.1%)	0/2 (0%)	0/4 (0%)
Substitutions	0/17 (0%)	2/2 (100%)	4/4 (100%)
Pseudowords			
Errors	25/38 (65.8%)	25/38 (65.8%)	10/38 (26.3%)
Neglect errors	25/25 (100%)	13/25 (52%)	9/10 (90%)
Omissions	22/25 (88%)	3/13 (23.1%)	2/9 (20%)
Substitutions	1/25 (4%)	10/13 (76.9%)	8/9 (80%)
Presence of USN	Yes	Yes	Yes
Error-type ND	omission-type	substitution-type	substitution-type

Table 5.1. Demographic features, baseline assessment of USN and ND (Vallar et al., 1996) for three out of six patients. F, frontal lobe; P, parietal lobe; T, temporal lobe; M/F, male/female; Scores: (i) cancelation tasks: omission errors; (ii) Wundt-Jastrow area illusion test: "unexpected" responses; (iii) reading task: the number of sentences in which patients showed left-sided errors; 16cm lines bisection error (mm). *Pathological score [Wundt–Jastrow and sentence reading are defined on the basis of the norms provided by the screening battery (Pizzamiglio et al., 1989)].

Patients were diagnosed with USN if they obtained pathological scores on at least two of the five tests included in the diagnostic battery, and they were considered as having ND if 50% or more of their errors were classified as neglect errors in both word and pseudoword reading tasks. All of the three patients (MA, EP and NR) showed a moderate to severe USN and all of them showed reading difficulties that can be classified as ND. MA's reading deficit was mostly characterized by omission errors (omission-type ND), whereas EP and NR's reading deficits were substitutions (substitution-type ND). Results of the assessment of visuals spatial neglect and neglect dyslexia for patients MA, EP and NR are summarized in Table 5.1.

Patients RE, AS and CG were recruited later and underwent a different diagnostic battery, in order to assess their cognitive functions. Other than the tests described above, the battery included also the following tests:

(a) *Bells cancellation* (Gauthier, Dehaut & Joanette, 1989.). The patient is asked to circle with a pencil all 35 bells embedded within 280 distractors (houses, horses, etc.). All drawings are black and the sheet of paper is placed at the patient's midline. The objects are presented in an apparently random order, but they are actually equally distributed into 7 columns containing 5 targets and 40 distractors each. Of the 7 columns, 3 are on the left side of the sheet, 1 is in the middle, and the remaining are on the right. The total number of circled bells is recorded and the maximum score is 35. Typically, an omission of 6 or more bells on the left half of the page indicates USN, and in the case of healthy participants the maximum difference between omissions in the two sides is 4 targets (Vallar et al., 1994).

(b) *Boston naming test* (Kaplan, Goodglass & Weintraub, 1983). It consists of 60 line-drawn pictures presented with increasingly difficulty (e.g., from "tree" to "abacus"). The patient is asked to name each picture and is given 20 seconds to name the item correctly. Phonemic cues are given after a failure to respond or an incorrect response. The total number of item correctly named is recorded and the maximum score is 60. A score below 42 is considered as pathological.

(c) *MOCA* (Nasreddine, 1996). This test is a screening tool for individuals with mild cognitive dysfunction. The test assesses 8 domains of cognitive functioning: attention and concentration, executive functions, memory, language, visuo-constructional skills, conceptual thinking, calculations, and orientation. The maximum score is 30 and a score below 26 indicates the presence of a mild cognitive impairment.

(d) *VOSP* (Lezak, Howieson, Loring, Hannay & Fischer, 2004). This test consists of eight sub-tests each designed to assess a particular aspect of object or space perception, while minimising the involvement of other cognitive skills. Each sub-test has its own cut-off score.

(e) *Verbal judgments* (Spinnler & Tognoni, 1987). This test assesses patient's abstract and logical reasoning and it consist of 4 parts: differences, proverbs, absurdity, and categorisation. The maximum score is 60 and a score below 32 is usually interpreted as pathological.

RE and AS did not show USN, while CG showed a shift of the manual bisection to the right side, but no USN at the cancellation task; all of them manifested some further visual impairments in object or space perception. Abstract and logical reasoning was appropriate for all the three patients, even though they showed a pathological score to the MOCA (mainly because of visuo-spatial dysfunctions). Results of the neuropsychological assessment for patients RE, AS and CG are summarized in Table 5.2.

	RE	AS	CG
Gender	M	M	M
Age	74	78	68
Education	10	12	17
Lesion site	FPO dx	O dx - C sx	PT sx
Neglect assessment			
Bells cancellation			
Left (/27)	4	3	0
Right (/27)	0	4	0
Bisection (mm)	-	0.0	13.6*
Neuropsychological assessment			
Boston naming test (/60)	50	45*	47*
MOCA (/30)	23*	22*	24*
VOSP			
Screening test (/20)	18	20	19
Incomplete letters (/20)	17	20	19
Progressive silhouettes (/20)	14*	14*	11*
Dot counting (/10)	8*	10	10
Position discrimination (/20)	20	20	10*
Number location (/10)	10	10	9
Cube analysis (/10)	5*	10	10
Verbal Judgments (/60)	38	45	47

Table 5.2. Demographic features, baseline assessment for unilateral spatial neglect and Neglect dyslexia assessment (Vallar et al., 1996) for three out of six patients. F, frontal lobe; P, parietal lobe; T, temporal lobe; O, occipital lobe; C, cerebrellum; M/F, male/female.

5.3. Experiment 4a – Neglect dyslexia assessment

5.3.1. Materials and methods

Participants

All six patients underwent this study in order to characterize their type of reading errors, according to the letter-based analysis used by Martelli et al. (2011).

Apparatus, stimuli and procedure

A list of 40 pseudowords was used. This list was created by interchanging the syllables of real words (taken from Burani et al., 2002; http://www.istc.cnr.it/grouppage/lexvar) in random positions, in order to preserve pronunciation and minimize word similarity. Pseudowords varied in length, from 5-to-8-letters (10 stimuli for each length). The stimuli were written in capital Courier New font, which is characterized by consistent letter spacing, and letter size was kept constant (40 pt) and subtended 1.0°. Pseudowords were written in black and presented on a white background.

On each trial, patients were shown two little squared fixation points, vertically displaced 1.5° apart, in the center of the screen. These fixations marks remained on the screen for the entire experimental session. Stimulus onset was triggered when the patient steadily fixated in the centre of the area between the two squared marks for at least 50 ms. Each stimulus was presented in the centre of the screen within the fixation marks (i.e., the central letter of each stimulus was vertically aligned with the fixation marks), and remained on the screen until the onset of the patient's response. There was no time constraint for responding, and patients were asked to read aloud each stimulus as accurately as possible. Pseudowords appeared in randomized order across participants. Responses were digitally recorded and errors were scored after listening to the recorded track later.

Statistical analyses

Letter omissions and substitutions errors for each stimulus were measured. Following Martelli et al. (2011), a letter-based approach treating each letter in the word independently was applied. This procedure was preferred against the one of Caramazza and Hillis (1990), because of the strictness of this last criterion. Indeed, Caramazza and Hills's criterion excludes substitution errors occurring on the right side of the stimulus from the analysis, and gives a less detailed description of performance. Therefore, we measured the omission and substitution errors over the entire stimulus, following a letter-based analysis.

Reading errors were then modeled separately for omissions and substitutions. Following Martelli et al. (2011), the proportion of omission errors produced by the patients was fitted by a three parameters exponential decay model, by using the following equation:

$$P(omission) = a + be^{(-cx)}$$

where *a* is the offset, *b* is the amplitude, and *c* is the rate of change. Furthermore, the proportion of substitution errors has been fit by the sum of two Gaussian distributions, according to the following equation:

$$P(substitution) = a + be\ (-(x-c)^2/d^2\ )$$

where *a* is the offset, *b* is the area under the curve, *c* is the center of the distribution, and *d* is the width.

The eye movement recording during the task ensured that the first fixation landed on the centre of the pseudowords. According to perceptual crowding, the identificability of letters falling around the fixation and of the external letters (that only have one flanker nearby) should be spared when letter size is well above acuity, as in the present case. Letters in intermediate positions should be misidentified because of crowding (Martelli et al., 2011). Thus, a two Gaussian distributions model would be the best model in describing the substitutions data, with picks on the left and right side of the centrally fixated string. On the contrary, the distribution of omission errors, which should be determined by USN and oculo-motor dysfunction, should be best described as a unilateral exponential decay.

5.3.4. Results

Figure 5.1. reports the proportion of omission and substitution reading errors made by the patients as a function of letter position. The figure shows the following pattern: MA made a great number of omissions only on the left side of the stimulus, whereas all other patients (EP, NR, RE, AS and CG) made fewer errors, mostly substitutions, and more evenly distributed along the entire stimulus. The analysis of the error distribution in this group of patients showed also that substitutions and omissions have different shapes, as expected.

Indeed, in the case of omissions the exponential decay captures a large proportion of variance for MA (R^2 = 0.94), EP (R^2 = 0.96), NR (R^2 = 0.93) and RE (R^2 = 0.99), whereas AS and

CG did not make omission errors at all. Furthermore, omission errors were confined to the left side of the stimulus, as predicted by USN.

By contrast, substitution errors showed a substantially different pattern. Their pattern is well captured by the bimodal distribution for EP (R^2 = 0.97), NR (R^2 = 0.94), RE (R^2 = 1.00), AS (R^2 = 0.99), and CG (R^2 = 1.00). Substitution errors were symmetrically distributed around the fixation point (for example EP’s picks were at letter position –3.14 and 2.67), sparing the external letters that only had one flanker nearby (as predicted by crowding). In the case of MA, the distribution was captured by a single Gaussian with a pick around letter position -1 (R^2 = 0.88).

These data are in agreement with previous findings by Martelli et al. (2011) in that patients (e.g. AR and DNA, in their study) characterized by a majority of substitutions tipically make fewer and more distributed errors. Additionally, the data indicated that omissions, but not substitutions, have a clear left-lateralization typical of USN disorder.

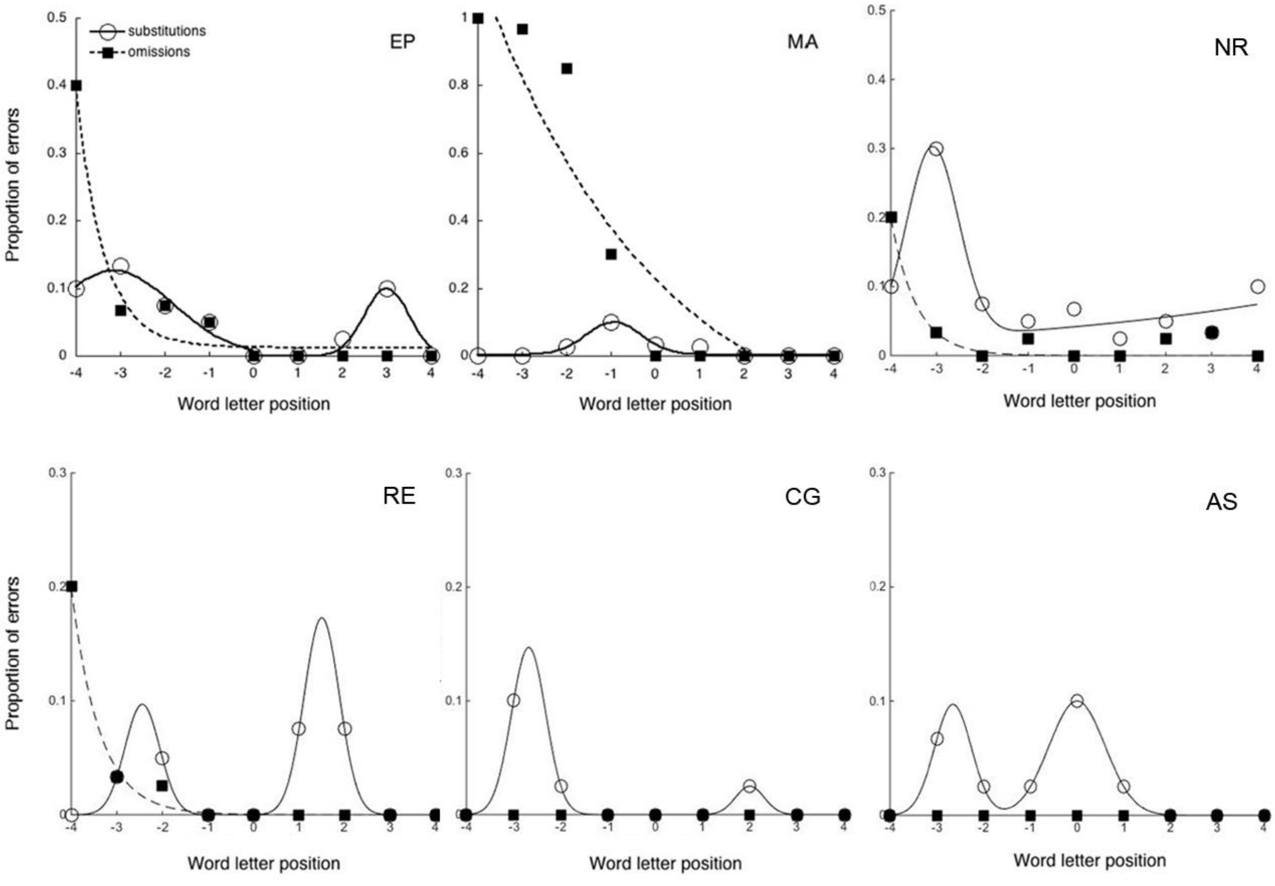

Figure 5.1. The proportion of reading errors made by the six patients, divided into substitutions and omissions as a function of letter position.

Thus, results of experiment 5a showed that among the six patients included in the study, one (MA) showed an omission-type ND, since her performance was characterized mostly by omission errors only on the left side of the stimulus, whereas five out of the six patients (EP, NR, RE, AS and CG) showed a substitution-type ND, and their errors were mostly substitutions distributed around the centre of the stimulus.

5.4. Experiment 4b – Eye movement in a non-verbal task

5.4.1. Materials and methods

Participants

Five patients (MA, EP, NR, CG and AS) participated in this study. A group of 13 healthy volunteers (4 males, mean age = 70.62 ± 9.83, mean education level = 12 ± 4.55) matched for age and education level to the patients were also tested, as control group.

The aim of the present study was to assess patients' abilities to execute fine eye-movement during a non-reading task that simulates the sequential reading gaze behaviour, accounting for their reading difficulties. Indeed, Primativo et al. (2013) demonstrated that the prevalence of omission errors in ND is associated with impairment in eye-movement pattern in both reading and non-reading tasks. Thus, the same saccadic task used by Primativo et al. (2013) was used, in which patients had to follow a moving dot with their eyes on the horizontal meridian along five different spatial positions, both right to left and left to right.

Apparatus, stimuli and procedure

A black dot subtending 0.2° of visual angle and displayed on a white background, appeared along the horizontal meridian in five consecutive positions, 4.0° away from each other, according to a synchronous paradigm (i.e., no gap). The dot appeared sequentially in the five positions and remained in the two extreme positions for 2 s, whereas in the three central ones for 1 s. The sequence started with the extreme left dot and then each dot appeared in turn until the extreme right dot appeared; afterwards the reverse sequence took place. The rightward and leftward sequences were repeated twice during each trial. Three trials were administered. Patients were required to follow the dot as quickly and as accurately as possible. Monocular eye movements were recorded in binocular vision via an SR Research Ltd., Eye Link 1000 eye tracker (SR Research Ltd., Mississauga, ON, Canada) sampling at 1000 Hz, with spatial resolution of less than 0.04°.

Head movements were avoided by using a headrest. Patients sat 57 cm away from a 1700 CRT monitor, and a standard nine-point calibration procedure was run before collecting the data. The calibration targets were presented randomly in different positions on the screen. The experimental task started immediately after calibration.

Statistical analyses

Accuracy (percentage of fixations on the dot when it was on the screen) and saccade latencies (time elapsed from the appearance of the dot to the beginning of the saccade) were measured and are summarized in Table 5.3 and Table 5.4. We excluded from the analysis both the fixations made on the first dot in the sequence and anticipatory saccades (i.e. saccades starting before the appearance of the following dot). We also excluded fixations that were far from the target with respect to its vertical axis (i.e. over 2 standard deviations calculated on the vertical fixation positions of the control group). The remaining fixations were considered as “accurate” if they fell no more than 1 deg of visual angle away from the actual target.

Eye movement data were processed using EyeLink Data Viewer software (SR Research Ltd.,Mississauga, ON, Canada) and patients’ data were compared to those of the control participants, by means of Crawford statistics (Crawford et al., 1998; Crawford & Garthwaite, 2002).

5.4.4. Results

The analyses of accuracy (see Table 5.3) showed that MA (left-to-right: t(12) = -5.785, p = .000; right-to-left: t(12) = -8.402, p = .000; all: t(12) = -6.996, p = .000) and CG (left-to-right: t(12) = -4.370, p = .000; right-to-left: t(12) = -6.650, p = .000; all: t(12) = -5.626, p = .000) were significantly less accurate than controls both when the dot was moving rightward and leftward, whereas EP (left-to-right: t(12) = 1.579, p = .070; right-to-left: t(12) = 1.799, p = .097; all: t(12) = 1.713, p = .112), NR (left-to-right: t(12) = 0.246, p = .405; right-to-left: t(12) = 0.751, p =. 233; all: t(12) = 0.486, p = .318), and AS (left-to-right: t(12) = -0.993, p = .170; right-to-left: t(12) =v1.485, p = .163; all: t(12) = -0.168, p = .435) were not significantly different from controls.

	DOT DIRECTION					
	Left-Right		Right-Left		All	
	% accuracy	*latencies*	*% accuracy*	*latencies*	*% accuracy*	*latencies*
Controls (SD)	86,73 (8,10)	151,78 (33)	86,95 (6,99)	161,88 (38)	86,88 (7,38)	157,49 (36)
MA	38,10**	376,70**	26,00**	433,00**	33,30**	408,90**
EP	100,00	252,00*	100,00	240,00	100,00	246,00*
NR	88,80	126,33	92,40	270,86**	90,60	195,46
AS	78,38	130,48	97,72	140,11	85,59	135,90
CG	50,00**	126,33	38,71**	143,24	43,79**	135,52

Table 5.3. Comparisons between the accuracy (% correct) and saccade latencies (ms) of each patients and the thirteen controls, in the conditions where the dot moved from left to right, from right to left, and in the two conditions together. Significance level: * p<0.05, ** p<0.01.

The analyses of accuracy for the dot position (see Table 5.4.) confirmed that MA (first: t(12) = -6.757, p = .000; second: t(12) = -6.360, p = .000; third: t(12) = -5.428, p = .000; fourth: t(12) = -2.178, p = .025; fifth: t(12) = -4.637, p = .000) and CG (first: t(12) = -7.975, p = .000; second: t(12) = -5.071, p = .000; third: t(12) = -2.102, p = .029; fourth: t(12) = -3.634, p = .002; fifth: t(12) = -1.789, p = .050) were less accurate at each dot position, whereas no dot positions were different from controls in the case of EP's (first: t(12) = 1.117, p = .143; second: t(12) = 1.356, p = .100; third: t(12) = 1.160, p = .134; fourth: t(12) = 0.965, p = .177; fifth: t(12) = 1.268, p = .114), NR's (first: t(12) = -0-014, p = .494; second: t(12) = 0.199, p = .423;

third: t(12) = 0.458, p = .328; fourth: t(12) = 0.021, p = .492; fifth: t(12) = 0.854, p = .205) and AS' fixations (first: t(12) = -1.454, p = .172; second: t(12) = -0.423, p = .340; third: t(12) = -0.596, p = .281; fourth: t(12) = 0.239, p = .408; fifth: t(12) = 1.268, p = .114).

	DOT POSITION (%accuracy)				
	1	2	3	4	5
Controls (SD)	88,15 (10,22)	88,28 (8,33)	86,79 (10,97)	89,78 (10,21)	78,53 (16,32)
MA	16,70**	33,30**	25,00**	66,70*	0,00**
EP	100,00	100,00	100,00	100,00	100,00
NR	88,00	90,00	92,00	90,00	93,00
AS	72,73	84,62	80,00	92,31	100,00
CG	3,57**	44,44**	62,86*	51,28**	48,39*

Table 5.4. Comparisons between the accuracy (% correct) of each patient and for the controls, for each dot position. Significance level: * p<0.05, ** p<0.01.

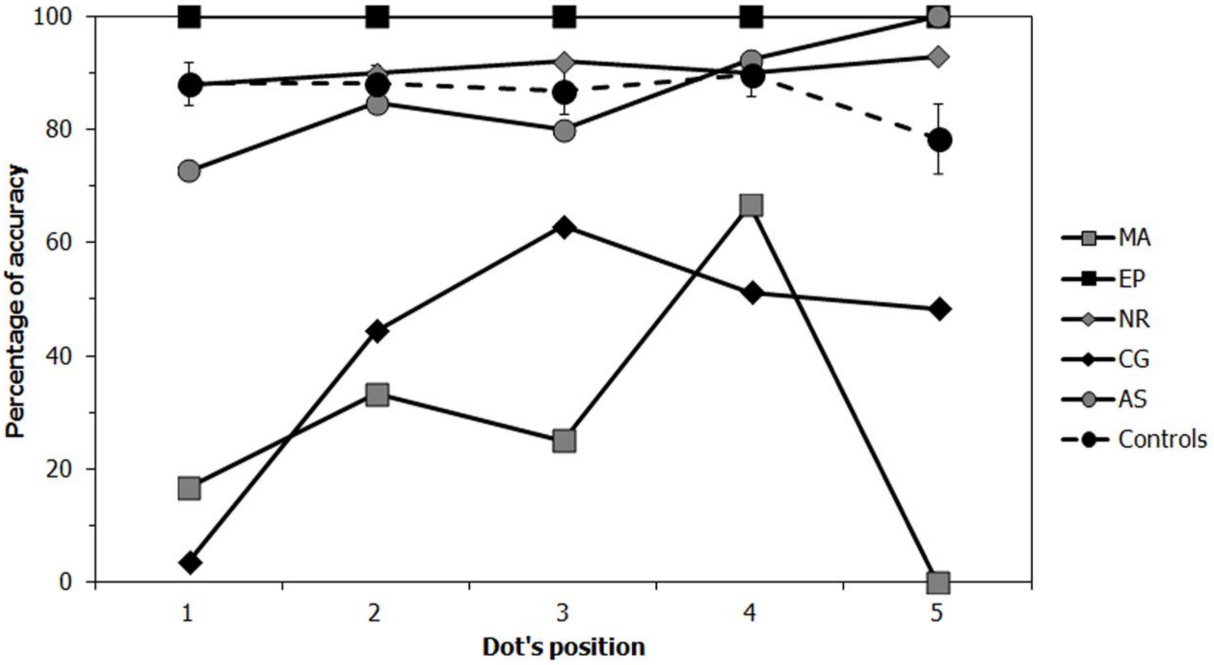

Figure 5.2. The mean percentage accuracy in the non-verbal saccadic task (following a dot moving from left to right and from right to left) made by the five patients and controls (vertical bars indicate ± 1 standard error of the mean).

The analysis on the saccade latencies (see Table 5.3.), by contrast, showed that MA was significantly slower both when the dot was moving rightward and leftward (left-to-right: t(12) = 6.568, p = .000; right-to-left: t(12) = 6.875, p = .000; all: t(12) = 6.730, p = .000), whereas CG (left-to-right: t(12) = -0.743, p = .236; right-to-left: t(12) = -0.475, p = .322; all: t(12) = -0.588, p = .284), who was impaired in accuracy, was comparable to controls. AS was not significantly different from controls in saccades (left-to-right: t(12) = -0.622, p = .273; right-to-left: t(12) = -0.552, p = .296; all: t(12) = -0.578, p = .287), whereas EP and NR were slightly slower than controls; indeed, EP was slower when the dot was moving rightward and in the overall latency (left-to-right: t(12) = 2.926, p = .006; right-to-left: t(12) = 1.981, p = .071; EP all: t(12) = 2.369, p = .035), whereas NR was slower only when the dot was moving leftward (left-to-right: t(12) = -0.743, p = .236; right-to-left: t(12) = 2.764, p = .009; EP all: t(12) = 1.016, p = .165).

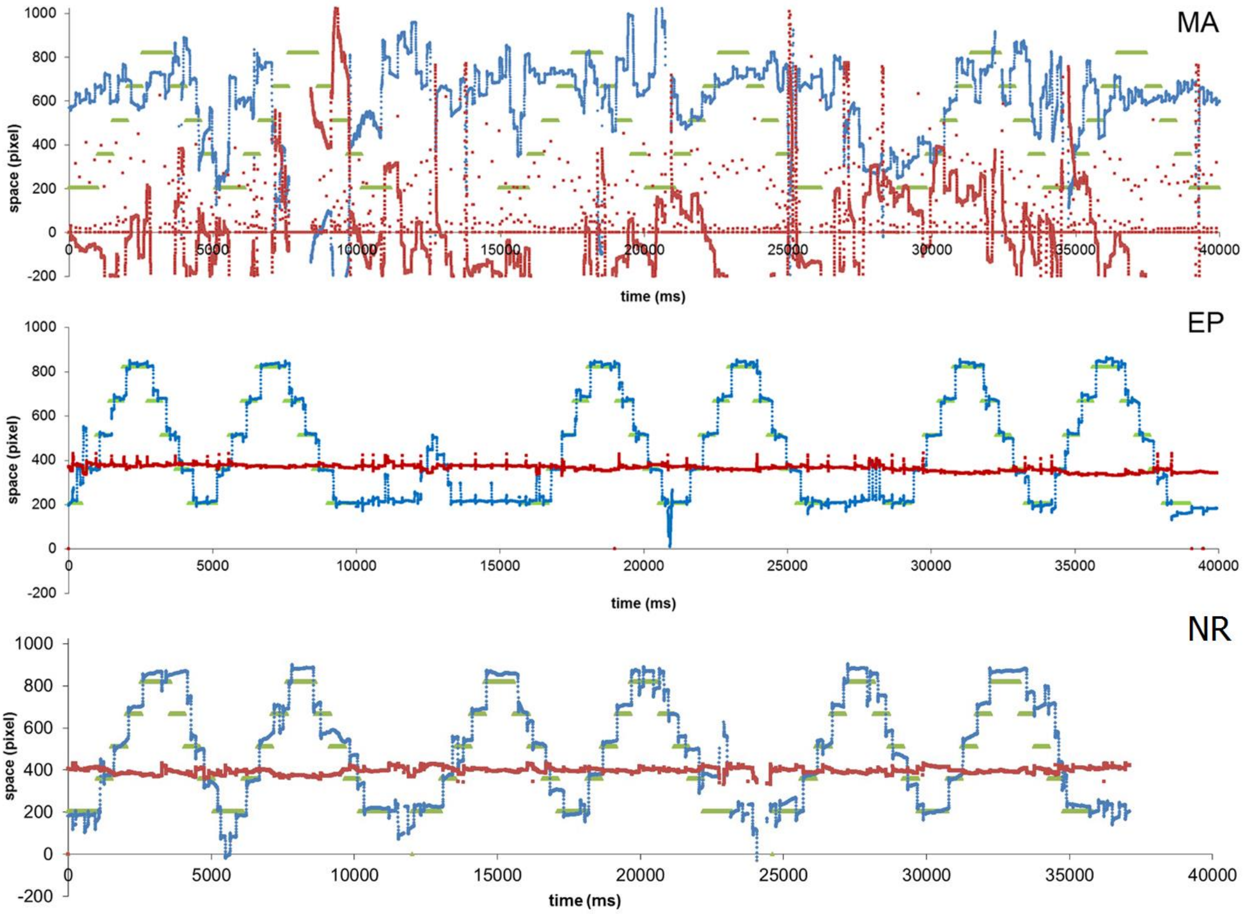

Figure 5.3. Example of patients' (MA, EP and NR) ocular behaviour in the non-verbal saccadic task. The green lines indicate the dot positions, the red lines indicate the y coordinate of the eye movements and the blue lines the x coordinate.

The results of Experiment 4b showed that MA, the patient making mainly omission errors in reading, was profoundly impaired (both in terms of accuracy and saccade latency) in performing a simple saccadic task on the horizontal axis. By contrast, CG was impaired in terms of accuracy, but not in the latency of his saccades, suggesting that his impairment is milder compared to MA's. On the contrary, NR, AS, and EP did show a preserved performance at the same saccadic task (even though with slower saccades sometimes). Taken together, these results suggest that substitution-type ND is a qualitatively different disorder from omission-type ND. In fact only the patient affected by omission-type ND was impaired in this saccadic task, whereas three out of four patients affected by substitution-type ND showed normal performance. However, it has to be mentioned that CG, the only substitution-type ND patient who failed at this saccadic task, is our only patient with a left hemisphere lesion and a rightward bisection bias.

5.5. Experiment 4c – Eye movement pattern in reading tasks

5.5.1. Materials and methods

Participants

Patients EP and NR participated in this study. Five healthy participants (3 males, mean age = 62 ± 7.62, education level = 13 ± 3.54), matched for age and education level were also tested.

In this study, inter-letter spacing was manipulated to assess the effect of spacing on both reading performance and eye-movement pattern. Indeed, previous studies demonstrated that letter recognition can be restored by increasing inter-letter spacing (e.g. Pelli et al., 2004; Whitney & Levi, 2011), and that inter-letter spacing also influences normal word reading by increasing fixations duration (Bricolo et al., 2015). In particular, if substitution errors were due to an excessive integration of features, independently of USN, increasing the inter-letter spacing would decrease the numbers of substitutions, without affecting omission errors.

Apparatus, stimuli and procedure

As in Experiment 4a, pseudowords were created so as to preserve pronunciation and minimize word similarity. Two lists of 40 5-to-8-letters pseudowords (10 for each length) were created. The stimuli were written in capital Courier New font and letter size was kept constant (40pt) and subtended 1.0 deg. Letter spacing was kept constant in the first list (unspaced condition), whereas in the second list (spaced condition) inter-letter spacing was manipulated so that it increased exponentially as the letter moved away from the centre of the screen. Pseudowords were used because previous studies suggest that, rather than words, they may be more suitable stimuli for assessing neglect dyslexia (e.g., Riddoch, Humphreys, Cleton, & Fery, 1990; Behrmann et al., 1990; Arduino, Burani, & Vallar, 2002, 2002; Martelli et al., 2011; 2010).

Eye-movements were recorded via an SR Research Ltd. EyeLink 1000 eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada) sampling at 1000 Hz, with spatial resolution of less than 0.04 deg. Although viewing was binocular, only the right eye was tracked. Head movements were avoided by using a headrest. Participants sat 57 cm away from a 17-inch computer screen. Before the experiment began, participants underwent a standard nine-point calibration procedure. The calibration started with the presentation of a white dot in the centre of a black screen, which afterward moved randomly around the edge of the screen. The calibration was accepted when the worst error point in the calibration was less than 0.75° and the average error for the nine-points less than 0.5°. The Experiment was controlled by the Experiment Builder software (SR Research Ltd., Mississauga, Ontario, Canada) and each experimental task started immediately after calibration.

On each trial, patients were shown two fixation marks (squared dots) vertically displaced 1.5 deg apart in the centre of the screen, which remained on the screen for the entire experimental session. Stimulus onset was triggered when the patient steadily fixated in the centre of the area between the two squared marks for at least 50ms. Each stimulus was presented in the centre of the screen between the fixation marks (i.e. the central letter of each stimulus was vertically aligned with the fixation marks) and remained on the screen for 1 second, even though there was no time constraint for responding. Patients were asked to read aloud each stimulus as accurately as possible. Pseudowords appeared in randomized order across participants. Responses were digitally recorded and errors were scored offline. The two patients and controls underwent firstly the unspaced condition and later the spaced one.

Statistical analyses

Reading errors were classified as omissions or substitutions according to a letter-based analysis, and measured separately for the left and right part of the stimulus. Omission and substitution reading errors of controls were submitted to a two-way repeated measures ANOVA with *Side of errors* (left, middle and right) and *Condition* (unspaced and spaced) as within-subjects factors. Data from patients EP and NR, instead, were compared to controls' data by using Crawford and Garthwaite's (2002) comparisons.

Eye movement data were processed using Eye Link Data Viewer software (SR Research Ltd., Mississauga, ON, Canada) and five eye-movement parameters were measured individually for each participant: first fixation position and duration, mean fixation duration, mean number of fixations per item (separately for the entire string and for the left- and right- sided group of letters of the stimulus), and fixation accuracy per item. First fixation position was determined by attributing zero value to the central letter, negative values to the letters on the left (i.e. the first letter on the left was coded as -1, the second letter on the left as -2 and so on), and positive values to the letters on the right part of the stimulus. Mean number of fixations and mean fixation duration were computed separately for each item, and were based on all fixations performed after the stimulus onset and before the disappearance of the stimulus. Accurate fixations were computed by considering a fixation as "accurate" if it was no more than 1 degree of visual angle away from the nearest letter. Finally, the proportion of fixations that actually fell on the letters composing the stimulus, with respect to the total number of fixations made all over the screen, was computed.

Fixation position and fixation duration data were used as dependent variables in a dependent t-test with *Spacing condition* (unspaced vs. spaced) as within-subject factor. Mean fixation duration, mean number of fixations, and mean number of accurate fixations per item were submitted to a two-way repeated measures ANOVA with *Condition* (unspaced vs. spaced) and *Side of stimulus* (left vs. right) as within-subject factors. Again, data from patients EP and NR were compared to controls' data by using Crawford and Garthwaite's (2002; 2010) comparisons.

5.5.2. Results

Reading errors

Controls made fewer errors and mostly substitutions. The ANOVA on substitution errors highlighted a significant interaction between *Side of error* and *Spacing condition* ($F(2, 8) = 5.39$, $p = .033$, $\eta^2 = 0.154$), showing that controls made more substitutions on the right side of the stimulus in the spaced condition compared to the unspaced one. On the contrary, no significant effects were found for omission errors.

Both EP and NR made many errors, mostly on the left part of the stimulus. More interestingly, the error type was influenced by spacing condition. Indeed, EP and NR made more substitution errors in the unspaced condition, whereas in the spaced condition the increasing of the inter-letter spacing increased the omission errors and reduced substitutions. Crawford and Garthwaite's (2002) comparisons confirmed that both patients made significantly more omission and substitution errors than controls in both the unspaced and spaced conditions (all $t > 2$ and all $p_s < .001$). Furthermore, by computing the difference between the two conditions in order to test for a dissociation (Crawford & Garthwaite, 2005; Crawford, Garthwaite & Porter, 2010), EP and NR showed a decreased number of substitution errors, significantly larger compared to the controls, from the unspaced to the spaced condition (EP: t(4) = 7.513, p = .000168, Z-DDC = 17.39; NR: t(4) = 5.509, p = .00719, Z-DDC = 9.448), and a significant increase of omission errors (EP: t(4) = 9.717, p = .00063, Z-DDC = 17.01; NR: t(4) = 3.304, p = .02982, Z-DDC = 4.358).

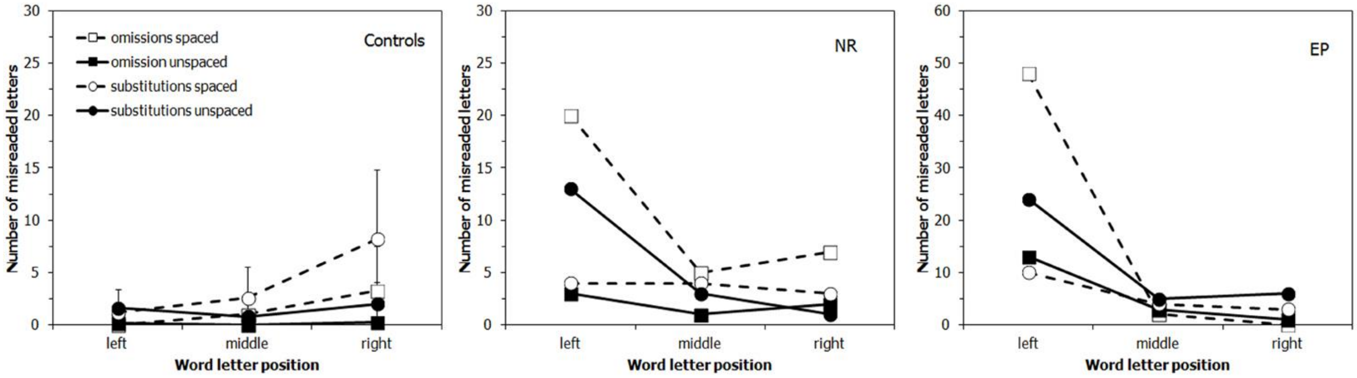

Figure 5.4. Results of experiment 4c. Mean number (and standard deviation) of letters omitted and substituted in the left, middle and right portion of the stimuli by controls, EP and NR.

Eye-movement pattern

The analysis on the first fixation (see Figure 5.5.) showed a significant effect of the *Condition* on the first fixation position (t(4) = 7.12, p < .005), but not on the first fixation duration (t(4) = 0.089, p = .934): controls' first fixation fell more on the left side of the stimulus in the spaced condition (-0.88) compared to the unspaced one (-1.90), whereas the first fixation duration was similar in the two conditions (unspaced 226 ms and spaced 224 ms). Conversely, EP's first fixation fell on the right side of the stimulus in both the unspaced (0.61) and spaced conditions (0.87), whereas NR's first fixation fell on the left side of the stimulus in the unspaced condition (-0.49) and on the right side in the spaced one (0.05). Furthermore, compared to controls, EP and NR made significantly longer first fixations in both the unspaced and spaced conditions (EP unspaced: 374 ms, t(4) = 6.113, p = .00181, Z-CC = 6.697; EP spaced: 270 ms, t(4) = 1.082, p = 0.17012, Z-CC = 1.185; NR unspaced: 471 ms, t(4) = 10.095, p = .00027, Z-CC = 11.058; NR spaced: 328 ms, t(4) = 2.464, p = .03468, Z-CC = 2.70). Finally, both EP and NR showed a significant decrease in the first fixation duration from the unspaced condition to the spaced one

(EP: 374 and 270 ms, respectively, t(4) = 4.029, p = .01575, Z-DCC = 6.626; NR: 328 and 471, respectively, t(4) = 5.452, p = .0055, Z-DCC = 10.048).

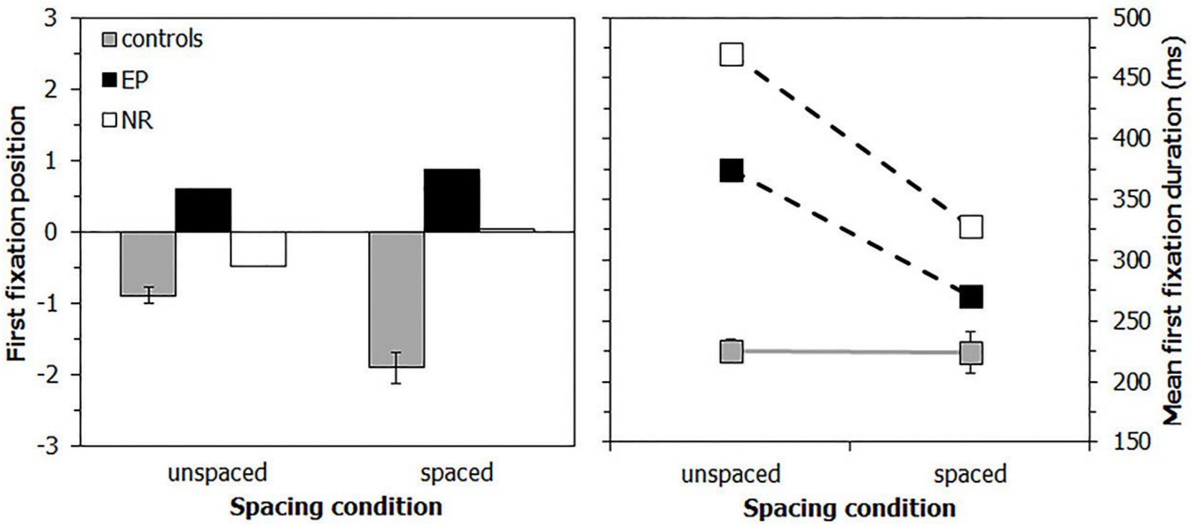

Figure 5.5. Results of first fixation position and duration by spacing condition for controls and EP.

A t-test for dependent samples on the mean number of fixations highlighted that controls made more fixations when the inter-letter spacing was increased compared to the standard inter-letter spacing (4.69 and 4.18 respectively, t(4) = -4.633, p < .01). An ANOVA with *Spacing condition* and *Side of stimulus* also showed a significant interaction between the two factors (F(1,4) = 7.83, p < .05), proving how controls made more fixations on the left side of the stimulus in the spaced condition, whereas in the unspaced condition their fixations were equally distributed along the entire stimulus. EP made significantly less fixations than controls in the unspaced condition, but not in the spaced condition, whereas NR made significantly less fixations than controls in both conditions (see Table 5.4.). Furthermore, EP's increase in the fixation number from the unspaced to the spaced condition was significant compared to controls (t(4) = 2.794, p = .049, Z-DCC = -4.399). On the other side, NR made the same number of fixations in both conditions (t(4) = 2.479, p = .06832, Z-DCC = 3.653).

The ANOVA on the mean fixation duration showed a significant effect of the *Side of stimulus* (F(1,4) = 28.28, p < .001), and a significant interaction between this factor and the *Spacing condition* (F(1,4) = 16.07, p < .05), highlighting that controls tended to make longer fixations on the right side of the stimulus in the unspaced condition. EP and NR, instead, made longer fixations compared to controls both on the left- and right-side of the stimulus. More interestingly, both EP's and NR's mean fixation duration was shorter in the spaced condition compared to the unspaced one (EP: 309 and 405 ms respectively, t(4) = 4.271, p = .01294, Z-DCC = 7.399; NR: 345 and 403 ms respectively, t(4) = 3.482, p = .02530, Z-DCC = 5.658), whereas controls tended to make fixations of almost the same duration in the two spacing conditions (unspaced 232 ± 22 and spaced 218 ± 32 ms).

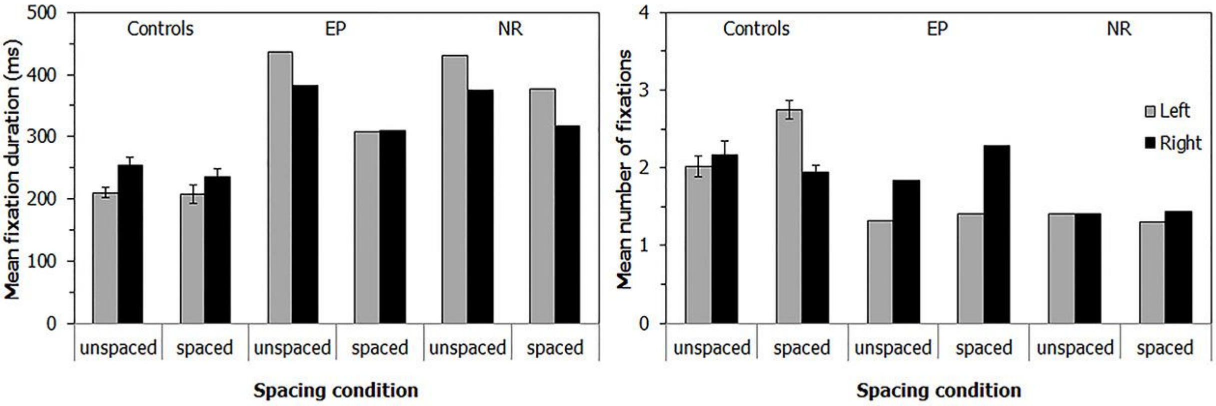

Figure 5.6. Results of mean fixation duration and mean number of fixations by spacing condition for controls and EP.

The analysis on the fixation accuracy showed that in the case of controls most fixations were accurate and the spacing condition did not affect their fixations accuracy (unspaced 92.70% and spaced 95.39%; t(4) = -1.095, p = .335). An ANOVA with *Side of stimulus* and *Spacing condition* as within-subject factors confirmed that neither the side of the stimulus (F(1,4) = 0.995, p = .384) nor the interaction between the two factors (F(1,4) = 2.147, p = 0.195) affected controls' fixations accuracy. As for EP's and NR's fixation accuracy, they did not significantly differ from controls neither in the unspaced condition nor in the spaced one.

The results indicated that increasing the inter-letter spacing proportionally to the eccentricity of the stimulus is effective in reducing substitution errors, by suppressing the crowding effect. Conversely, the increased inter-letter spacing increased omissions; a result of the stimulus extending farther into the neglected hemifield during this condition.

The results also indicated that the eye-movement pattern is sensitive to differences in the inter-letter spacing. Overall, EP and NR began to explore the stimulus from the right side (whereas controls started from the left side), they made fewer and longer fixations than controls, and showed a great proportion of accurate fixations. Furthermore, EP increased the number of fixations by reducing their length during the spacing condition.

	Unspaced			***Spaced***		
	Mean number of fixation	*Mean fixation duration (ms)*	*Accurate fixation*	*Mean number of fixation*	*Mean fixation duration (ms)*	*Accurate fixation*
Overall						
Controls	4.18 (0.31)	232 (22)	.927 (.07)	4.69 (0.26)	218 (32)	.954 (.02)
EP	3.27*	405**	.939	4.51	309*	.956
EP Effect size (Z-CC)	-2.948	7.818	0.169	-0.67	2.844	0.105
NR	2.82**	403**	1.00	2.74**	345*	0.99
NR Effect size (Z-CC)	-4.387	7.773	1.043	-7.500	3.969	1.800
Left-side						
Controls	2.01 (0.29)	210 (20)	.918 (.09)	2.74 (0.26)	207 (34)	.965 (.01)
EP	1.36	437**	.954	1.69**	309*	.964
EP Effect size (Z-CC)	-2.236	11.350	0.400	-4.141	3.000	-0.100
NR	1.41	430**	1.00	1.31**	377**	0.98
NR Effect size (Z-CC)	-2.069	11.000	0.911	-5.500	5.000	1.500
Right-side						
Controls	2.16 (0.39)	255 (12)	.933 (.06)	1.94 (0.20)	235 (33)	.936 (.02)
EP	1.91	383**	.928	2.82*	309*	.951
Effect size (Z-CC)	-0.649	10.667	-0.083	4.378	2.242	0.750
NR	1.41	376**	1.00	1.44*	317*	1.00*
NR Effect size (Z-CC)	-1.923	10.083	1.117	-2.500	2.485	3.200

Table 5.4. Eye-movements data from Experiment 4c and Crawford and Garthwaite (2002) comparisons' results. For each variable, EP and NR scores, controls' mean (and standard deviation in brackets) and effect sizes are reported. Significant levels: * p < .05, ** p <.01.

5.6. Experiment 4d – Optokinetic stimulation

5.6.1. Materials and methods

Participants

Patients MA, EP, and NR participated in this study. 10 healthy controls were also tested (4 males, mean age = 67.1 ± 8.13, mean education = 10.9 ± 4.53). The aim of this study was to verify the effect of OKS on neglect dyslexia, and in particular to assess the different sensitivity of omissions and substitutions to it. As mentioned before, OKS was chosen because it has the advantages of bottom-up techniques, specifically facilitating the displacement of oculo-motor exploration toward the neglected side of the space. Since omissions errors seem to be due to abnormal oculo-motor behaviour, whereas substitutions do not, a rehabilitation training that aims at restoring the normal eye-movement behaviour should be effective in reducing only omission errors.

Apparatus, stimuli and procedure

OKS consisted of random black dots of 0.75° in diameter moving from right to left with a speed of 11.3°/s, presented on a grey background of 16° cd/m^2 in luminance on a CRT1700 monitor screen (1024 x 768 pixels). Two lists of 30 pseudowords of different length (6-7-8 letters) were used (font: Courier New; font size: 22) in order to avoid learning and repetition effects. As in Experiment 4a, the two lists were constructed so as to preserve pronunciation, and were matched for length in terms of number of letters and syllables, bigram frequency, neighbourhood size, and first phonemes.

The patients were seated in a dark and silent room facing the monitor that was displaying the visual stimuli. Their heads were positioned in an adjustable head-and-chin rest so that the distance between their eyes and the screen was approximately 57 cm. The experiment and the recording of the responses were carried out with MatLab 7.13. The experimental session consisted of three parts: a pseudowords reading task before the OKS (a), 10 min of OKS (b), and a pseudowords reading task (with different pseudowords) after OKS (c). During OKS (b) the patient's task was to look at the screen with the moving dots, with the instruction not to fixate on any specific dots, whereas during each reading task (a) and (c) the patient had to read aloud the 30 pseudowords presented in the centre of the screen; the pseudowords were written in white on a grey background. No fixation point was used. There were no time constraints and the 30 pseudowords were presented in the same fixed sequence for both patients. Only reading errors were recorded.

Statistical analyses

The 10 controls made no errors in reading the pseudowords. Thus, given that the performance of healthy subjects showed a ceiling effect, the chi-square analysis was used to test whether the number of reading errors was significantly different between before and after OKS in each patient and for each type of error.

5.6.2. Results

In the pre-OKS condition MA misread 19 out of 30 pseudowords, omitting 25 letters in 19 pseudowords. In the post-OKS condition MA misread 12 out of 30 pseudowords, and in this condition she omitted 12 letters in the 12 misread pseudowords, showing a reduction of misread pseudowords from 63.3 to 40% ($\chi^2(1) = 5.136$, $p = 0.023$). According to a letter-based analysis, MA showed a significant reduction in the number of omitted letters in the post-OKS compared to the pre-OKS condition ($\chi^2(1) = 6.72$, $p = 0.0095$), whereas substitutions (pre-OKS: 1 and post-OKS: 0) were at ceiling level.

By contrast, EP did not show any significant differences in terms of the number of substituted letters ($\chi^2(1) = 0.08$, $p = 0.7728$) or omitted letters ($\chi^2(1) = 0.25$, $p = 0.6179$. He misread 14 out of 30 pseudowords in the pre-OKS condition, making 13 substitutions in 12 pseudowords and 5 omissions in 5 pseudowords. In the post-OKS condition EP misread 10 out of 30 pseudowords, substituting 11 letters in 10 pseudowords and omitting 3 letters in 3 pseudowords; he showed a reduction of omission errors from 16.7 to 10% ($\chi^2(1) = 1.816$, $p = 0.178$) and a reduction of substitution errors from 40 to 33.3%, ($\chi^2(1) = 0.671$, $p = 0.413$).

NR misread 10 out of 30 pseudowords in the pre-OKS condition, making 13 substitutions in 10 pseudowords and 1 omission in 1 pseudoword. In the post-OKS condition, NR misread 9 out of 30 pseudowords, making 12 substitutions in 9 pseudowords and 1 omission in 1 pseudoword, showing a reduction of substitution errors from 33.3 to 30% ($\chi^2(1) = 0.053$ $p = 0.819$) and no reduction of omission errors (pre-OKS: 1 and post-OKS: 1). According to a letter-based analysis, NR did not show any reduction of substituted letter between the pre- and post-OKS conditions ($\chi^2(1)= 0.04$, $p = 0.841$), whereas omissions were at ceiling level (pre-OKS: 1 and post-OKS: 1).

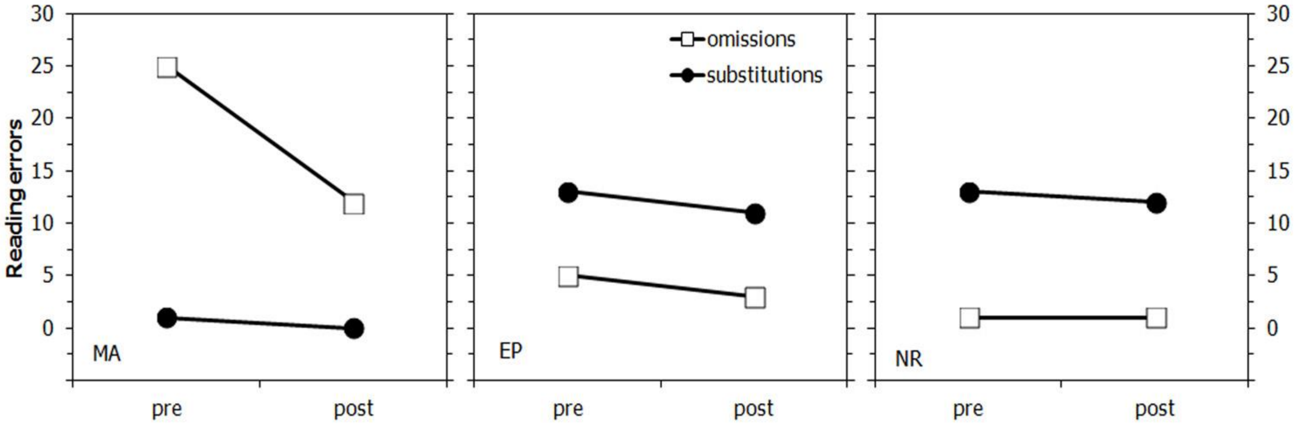

Figure 5.7. The absolute number of letters omitted (open square) or substituted (filled dots) while reading pseudowords, before and after OKS for patients MA, EP and NR.

Thus, both letter (see Figure 5.7.) and word based analyses showed a significant reduction only in MA's omission errors. These results confirmed that omissions and substitutions in ND are due to two different and independent mechanisms, and they corroborate the hypothesis of a dissociation between the two types of reading errors in terms of sensitivity to optokinetic stimulation, such that only omissions-type ND was affected by OKS.

5.7. Experiment 4e – The control of attentional focus

5.7.1. Materials and methods

Participants

Five out of the six patients (EP, NR, AS, CG and RE) participated in this study. Since two different versions of the cueing task were used (a first one for EP and NR, and a second one for AS, CG and RE), two different groups of healthy controls were recruited. The first was composed by 4 healthy volunteers (2 males, mean age = 58.75 ± 2.63, mean education = 11.75 ± 2.5) and served as EP's and NR's control group, whereas the second group was composed by 8 healthy volunteers (1 male, mean age = 76.00 ± 6.80, mean education = 11.37 ± 5.21), and it was used to evaluate patients AS', CG's, and RE's performance.

The aim of the current study was to assess patients' abilities in controlling attentional focus and in adjusting it according to the task demand. Particularly, this study aimed at verifying whether patients affected by substitution-type ND showed a further impairment in the control of focal component of spatial attention, which might be the cause of substitution errors in reading, by preventing the isolation of the letters from each other and their correct identification.

Apparatus, stimuli and procedure

Patients EP and NR (and their four controls) underwent the same detection task described in Chapter 2 (Experiment 1a) and based on the paradigm described in Maringelli & Umiltà (1998), whereas patients AS, CG, and RE (and their eight controls) underwent the same detection task described in Chapter 3 (Experiment 2a).

In the former case, the cue stimulus consisted of an empty square of variable size (3^o x 3^o or 6^o x 6^o, thickness of 0.1^0), outlined in white on a black background, and the target stimulus was a red dot (diameter of 0.4°). For patients AS, CG, and RE the target stimuli consisted of a capital letter T (font Sloan, colour black) of 1° x 1° degree of visual angle oriented upright. The cue could be represented by a red dot (diameter of 0.4°), or a small black square (1.2° x 1.2°, thickness of 0.1°), or a big black square (15° x 15°, thickness of 0.1°), or by the absence of a cue. In both the experiments, the cue stimulus was presented in the centre of the screen and the target stimulus was always shown in the centre of the cue. A response to the target stimulus was made by pressing the space bar on the computer keyboard.

Each trial started with a blank screen followed 1000 ms later by one of the possible cues (a big or small square for patients EP and NR, and a big square, or a small square, or a dot for patients AS, CG, and RE). The cue remained on the screen until the end of the trial (or until target appearance for patients AS, CG, and RE), whereas the target stimulus appeared after one of the following possible SOAs: 100, 500 or 700 ms for patients EP and NR, and 100 or 500 ms for patients AS, CG, and RE. The target stimulus remained on the screen until a response was given (or for a maximum of 2000 ms), after which the target disappeared and the next trial started. A baseline condition in which the target appearance was not precued was also included for patients AS, CG, and RE.

In 20% of trials (catch trials) no target stimulus was presented. Participants were instructed to fixate in the centre of the screen, to focus their attention inside the square, and to press the space bar as quickly as possible in response to the target stimulus. They were also instructed to refrain from responding on catch trials.

Patients EP and NR completed 120 trials, whereas patients AS, CG, and RE completed 160 trials. SOA conditions and cue types were presented randomly. At the beginning of the experiment, a practice session composed of 10 trials (or 25 for patients AS, CG, and RE) was run in order to let the participants familiarize themselves with the task and to practice with response modality.

Statistical analyses

Statistical analyses were performed using the software IBM SPSS Statistics 22. Reaction times (RTs) were adopted as the dependent measure. Trials with false alarms, i.e. responses to catch trials, and atypical RTs outliers (employing as a criterion 2.5 *SD*s above or below the mean within each participant) were discarded and not further analysed. Responses to catch trials were rare for both patients and controls (less than 1%) and were not further analysed.

Controls' data were analysed via a two-way repeated-measures ANOVA and the effects of interest were those associated with the experimental manipulations — that is, *Cue* (big square vs. small square or dot vs. small square vs. big square), *SOA* (100 vs. 500 vs. 700 ms or 100 ms vs. 500 ms) and their mutual interactions. The effect size in the ANOVA was also measured by computing the Eta Squared (η^2).

As in the previous chapter, we computed also the cue-size effect for all participants in order to obtain an amodal quantification of the advantage of narrowing the focal component. To this aim, we computed the Cohen's *d* between the big square and the small square conditions for each participant and each SOA condition. Then, the mean Cohen's *d* cue-size effect for each condition was tested with a one-sample t-test against the hypothesis that they were not significantly different from zero.

Finally, patients' cue-size effects were compared to those of controls, by means of Crawford statistics (Crawford et al., 1998; Crawford & Garthwaite, 2002).

5.7.2. Results

The ANOVA on EP's and NR's controls' RTs data showed a significant effect of *Cue* ($F(1,3) = 29.56$, $p < .05$, $\eta^2 = 0.225$) and a significant interaction between *SOA* and *Cue* ($F(2,6) = 5.83$, $p < .05$, $\eta^2 = 0.38$), whereas the main effect of *SOA* ($F(2,6) = 2.35$, $p = .176$, $\eta^2 = 0.305$) failed to reach significance. These results highlighted the presence of faster RTs in the small square condition (small square = 408 ± 22 ms, big square = 436 ± 20 ms), and planned comparisons showed that this advantage was smaller for the SOA of 700 ms compared to the SOA of 100 ms (F(1,3) = 8.78, p = .05). The analyses on the cue-size effect confirmed this trend; indeed, even though the cue-size effect was significantly greater than zero for all SOA conditions (100 ms SOA: t(3) = 4.24, p = .024; 500 ms SOA: t(3) = 4.67, p = .019; 700 ms SOA: t(3) = 4.77, p = .017), a dependent t-test proved that the cue-size effect at 700 ms (.138) was significantly smaller than both the cue-size effects of 100 (.694; t(3) = 3.10, p = .05) and 500 ms (.684; t(3) = 3.31, p = .045).

	RTs							
	SOA 100				SOA 500			
	none	*big*	*small*	*dot*	*none*	*big*	*small*	*dot*
Controls (SD)	543 (154)	562 (167)	503 (119)	571 (154)	521 (150)	511 (156)	497 (146)	539 (177)
RE	490	544	531	535	487	451	494	505
AS	454	449	513	476	464	567	509	489
CG	561	495	527	532	502	593	613	549
	SOA 100		SOA 500		SOA 700			
	big	*small*	*big*	*small*	*big*	*small*		
Controls (SD)	461 (14)	425 (19)	422 (23)	387 (29)	423 (27)	412 (26)		
EP	542	574	568	586	510	542		
NR	528	520	483	455	452	478		

Table 5.5. Mean reaction times (and standard deviations) for controls and the five patients in the cueing paradigm by SOA and Cue conditions.

Overall patients EP and NR did not show longer RTs compared to controls (t(4) = - 2.69, p > .05), and their RTs were not different between the big square and the small square conditions (513 ms and 526 ms respectively; t(1) = -0.874, p = 543). In fact both patients showed a smaller cue-size effect for all SOA conditions compared to controls; particularly, the difference between EP and the controls was significant at every level (100 ms SOA: t(3) = -2.336, p = .050; 500 ms SOA: t(3) = -2.437, p = .046; 700 ms SOA: -6.634, p = .003), whereas NR was significantly different from controls only in the case of the 700 ms SOA, even though his cue-size effect was reduced in every condition (100 ms SOA: t(3) = -1.724, p = .092; 500 ms SOA: t(3) = -1.437, p = .123; 700 ms SOA: -4.770, p = .009).

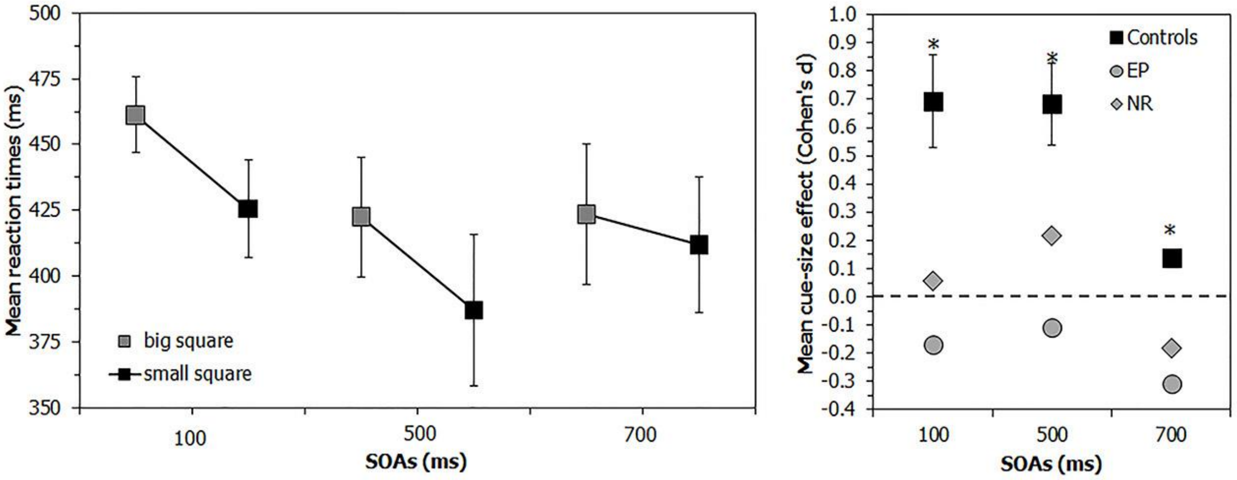

Figure 5.8. Results of the cueing paradigm for the four controls (for patients EP and NR). Mean reaction times (RTs) by SOA and Cue condition (left) and cue-size effect by SOA (right). Error bars= standard error of measure (S.E.M.).

The ANOVA on the eight controls' data of AS, RE, and CG showed as significant effects of both the main factors of *SOA* (F(1,7) = 8.93, p < .05, η^2 = 0.122) and *Cue* (F(3,21) = 5.87, p < .01, η^2 = 0.241), whereas their interaction was not significant (F(3,21) = 1.31, p = .298, η^2 = 0.039). RTs were faster in the 500 ms SOA condition (517 ms) than in the 100 ms condition (545 ms), and when the cue consisted of a small square. Planned comparisons on the main effect of *Cue* showed that the small square condition was significantly better than the dot condition (500 and 555 ms respectively; F(1,7) = 8.65, p = .022). Furthermore, data on the cue-size effect highlighted that the advantage of the small square was significant only when the SOA was 100 ms (.503; t(7) = 3.32, p = .013), whereas the mean cue-size effect was not significantly different from zero in the 500 ms SOA condition (.084; t(7) = .603, p = .565). The difference between the two SOA conditions was also significant (t(7) = 3.409, p = .011; see Figure 5.7.).

The RTs analysis showed that patients were not significantly slower than controls (514 ± 29 and 531 ± 150; t(9) = -0.191, p = 853), and that, again, patients' RTs were not influenced by the SOA (SOA 100 = 509 ms, SOA 500 = 519 ms, F(1,2) = 0.147, p = 738, η^2 = 0.19) nor the cue type (none = 493 ms, big square = 516 ms, small square = 531 ms, dot = 515 ms, F(3,6) = 4.64, p = .122 , η^2 = 0.153). The comparisons on the cue-size effect confirmed that patients AS, RE, and CG had some difficulties in controlling and adjusting the size of attentional focus. Indeed, both AS (t(7) = -3.789, p = .003) and CG (t(7) = -2.087, p = .038) showed a significantly smaller effect size at 100 ms SOA, whereas RE showed a smaller, even though not significantly different, cue-effect size than the controls' one (t(7) = -0.981, p = .180). With the 500 ms SOA, instead, RE (t(7) = -1.247, p = .126) and CG (t(7) = -0.442, p = .336) did not differ from controls (whose cue-size effect was equal to zero in this condition), and only AS (t(7) = 2.023, p = .041) showed a significant advantage of the small square.

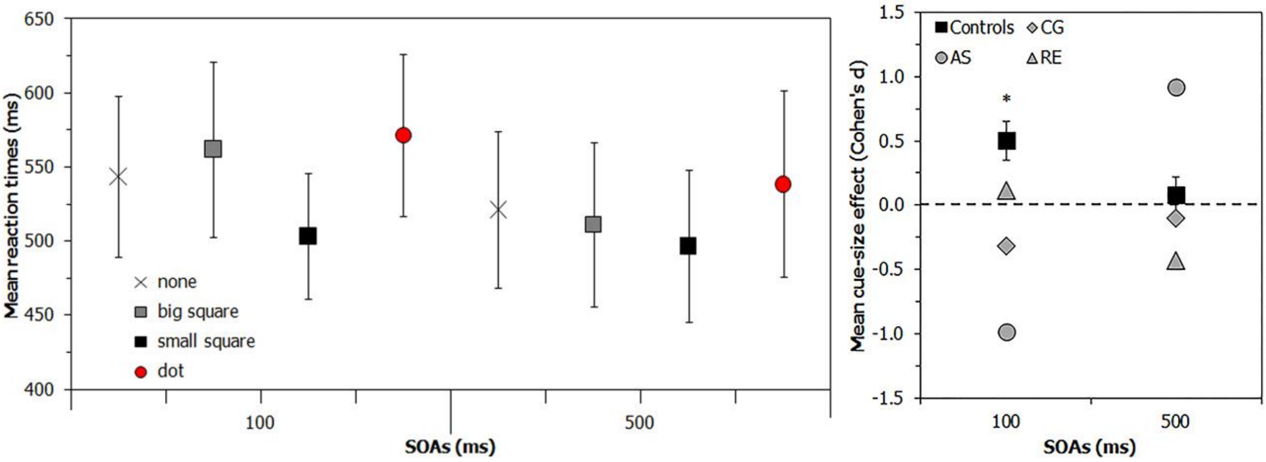

Figure 5.9. Results of the cueing paradigm for the eight controls (for patients AS, CG and RE). Mean reaction times (RTs) by SOA and Cue condition (left) and cue-size effect by SOA (right). Error bars= standard error of measure (S.E.M.).

Thus, both control groups showed an advantage in the detection of a target stimulus preceded by the presence of a small cue, which enables to reduce the visual space to focus. Particularly, according to the results of Experiment 1a and Experiment 2a, the effect of the focal component was stronger in the exogenous condition (i.e. short SOAs). More interestingly, all five patients showed some difficulties in controlling the attentional focus, i.e. smaller cue-size effects compared to controls. Indeed, CG, EP, and NR presented a deficit in both the exogenous (100 ms SOA) and the endogenous (500 and 700 ms SOA) conditions. By contrast, AS and RE exhibited a milder impairment, limited respectively to the shorter and longer SOAs.

The deficit in the control of attentional focus might be the cause of patients' performance in the reading task and the reason of their substitution errors: in particular, the failure in controlling attentional focus (both endogenously and exogenously) would prevent to "isolate" the letters from each other, and therefore their correct identification.

	Cue-size effect		
	SOA 100	SOA 500	SOA 700
Controls (SD)	.503 (.37)	.084 (.39)	-
RE	.118	-.432	-
AS	-.984**	.921$^{\#}$	-
CG	-.316*	-.099	-
Controls (SD)	.694 (.33)	.683 (.29)	.138 (.06)
EP	-.168*	-.107*	-.307**
NR	.058	.217	-.182**

Table 5.6. Mean cue-size effect (and standard deviations) for controls and the five patients in the cueing paradigm by SOA conditions. Significant levels: * p < .05 (negative direction), ** p <.01 (negative direction), $^{\#}$ p < .05 (positive direction), $^{\#\#}$ p < .01 05 (positive direction).

5.8. Discussion

The present chapter is aimed at investigating the mechanism underlying substitution errors in neglect dyslexia. A group of six patients has been tested in a series of experiments in order to investigate the relationship between substitution errors, crowding phenomenon and the control of focal attention, by assessing each patient's reading deficit, their oculo-motor behaviour, and their sensitivity to a specific sensory stimulation.

Experiment 4a showed that the reading impairment of five out of the six selected patients was characterized by a prevalence of substitution errors, whereas one patient (MA) had a reading performance affected by omission errors. According to Martelli et al.'s dual model (2011), omission errors were lateralized on the left part of the stimulus, whereas substitution errors were more distributed across the entire stimulus, sparing the centre and the first and last letters of the word, as predicted by crowding. Furthermore, substitution errors, being dependent on a perceptual integration mechanism, can occur in both the presence and the absence of USN, confirming their independence from USN (Martelli et al., 2011).

Experiment 4b assessed patients' ability to execute fine eye movements during a non-reading task, in which patients had to follow a moving dot with their eyes on the horizontal meridian along five different spatial positions, both right to left and left to right. The patient affected by omission-type ND (MA) was profoundly impaired in this task, both in accuracy and saccade latencies. On the contrary, three out of the four patients with substitution-type ND (EP, NR and AS) were unimpaired, showing performances comparable to those of the controls. The last patient affected by substitution-type ND (CG) presented a milder deficit compared to MA: his performance was impaired in terms of accuracy, but not in terms of saccade latencies. This patient was the only one with a left-hemisphere lesion and a crossed visuo-spatial deficit. Taken together, these results are in accordance with a previous study by Primativo et al. (2013) that demonstrated that the prevalence of omission errors in ND arises as a consequence of altered oculo-motor behaviour, which prevents the automatic execution of the fine saccadic eye movements implicated in reading. Furthermore, this deficit is independent of and additional to the USN impairment, and is detectable in both reading and non-reading tasks.

Results of Experiment 4b further highlighted that substitution-type ND is a qualitatively different disorder from omission-type ND. Indeed, some patients affected by substitution-type ND showed normal performance during the saccadic task, suggesting that the oculo-motor behaviour explanation cannot account for patients' reading difficulties, and that the mechanisms underlying substitution errors are to be sought elsewhere.

In Experiment 4c, the hypothesis that substitution errors are due to perceptual crowding was directly tested by recording the reading performance and the eye-movement patterns of patients affected by substitution-type ND during a pseudowords reading task. Specifically, the inter-letter spacing was manipulated (normal vs. proportional to the eccentricity inter-letter spacing), because previous studies demonstrated that crowding can be suppressed by increasing inter-letter spacing (e.g. Pelli et al., 2004; Whitney & Levi, 2011). Furthermore, other studies

(Bricolo et al., 2015; Paterson & Jordan, 2010; Bai, Yan, Liversedge, Zang & Rayner, 2008) have shown that increasing the inter-letter spacing induces more fixations of shorter duration. According to Bricolo et al. (2015), the increase in the fixation duration of unspaced stimuli is due to the role of attention, i.e. the involvement of attention needed to avoid crowding by isolating the single features of the letter for its correct identification. Thus, if substitution errors were due to an inappropriate integration of features independent of USN, increasing the inter-letter spacing would decrease the number of substitutions and fixation duration. According to this hypothesis, patients EP and NR reduced their numbers of substitution errors in the increased inter-letter spacing condition, confirming the effectiveness of this manipulation in suppressing crowding. Conversely, the increased inter-letter spacing increased omissions; a result of the stimulus extending farther into the neglected hemifield during this condition.

The analysis of eye-movement behaviour confirmed that the manipulation of inter-letter spacing affected the reading process. Firstly, both EP and NR showed a large proportion of accurate fixations, supporting the findings of Experiment 4b, that is, the ability to execute the fine eye movement needed for reading was spared in this patient and, more generally, in patients affected by substitution-type ND. Secondly, EP significantly increased his number of fixations from the unspaced to the spaced condition by shortening their duration, whereas NR made the same number of fixations in both conditions but their length was significantly reduced when the inter-letter spacing was increased; furthermore, EP made significantly fewer fixations than controls in the unspaced condition, but not in the spaced one. Thus, EP and NR made fewer and longer fixations in the unspaced condition, and this result could be due to their impairment in isolating the features of the single letters, resulting in substitution errors. On the contrary, in the case of the increased inter-letter spacing condition their impairment was less pronounced, resulting in fewer substitution errors and an eye-movement pattern similar to that of the controls. Hence, Experiment 4c demonstrated that substitution errors in ND are a consequence of altered features integration, which can be restored by increasing the inter-letter spacing.

Experiment 4d further extended the results of previous experiments by assessing the effect of optokinetic stimulation (OKS) on omission and substitution errors in neglect dyslexia. OKS is a technique that facilitates the displacement of oculo-motor exploration toward the neglected side of the space and, thus, the restoration of oculo-motor scanning. Experiments 4b and 4c demonstrated that only omission errors are due to abnormal oculo-motor behaviour in both reading and non-reading tasks, and, according to these results, in this experiment we found that only the patient affected by omission-type ND showed a significant reduction of errors after OKS. On the other side, substitution errors were not affected by this rehabilitation training, confirming that omissions and substitutions in ND are due to two different and independent mechanisms. Although Experiment 4d was not designed to be a full rehabilitation program (i.e. a single OKS session was used, whereas a full rehabilitation program would require almost 10 sessions of OKS), these results demonstrate that such a dissociation between omissions and substitutions could be extended to the effectiveness of rehabilitative procedures.

Finally, the last experiment of the present chapter (Experiment 4e) aimed to verify the hypothesis that the altered features integration process that produces substitution errors in ND is a consequence of the inability to control and adjust the size of attentional focus. In the previous chapters we demonstrated that attentional focus can be modified according to the task demands in foveal vision, under different temporal constraints. Results of Experiments 4e further confirmed this finding. Indeed, control participants showed an advantage in the detection of a target stimulus preceded by the presence of a small cue, which reduced the visual focus area; furthermore, this advantage was stronger when the SOA between the cue and the target stimulus was short (i.e. an exogenous condition). All five patients with substitution-type ND showed an impairment in the control of attentional focus: their cue-size effect was smaller than the mean cue-size effect of controls or reversed. In particular, CG, EP, and NR showed a deficit in both the exogenous and endogenous control of attentional focus, whereas AS and RE exhibited a milder impairment, limited respectively to the exogenous and endogenous conditions. Here we suggest that the deficit in the control of attentional focus might affect patients' performance during the reading task and cause their substitution errors. In particular, the failure to control attentional focus (both endogenously and exogenously) would prevent the "isolation" of letters from each other, and therefore would not allow the patients to correctly identify every single letter. Moreover, as further confirmed by the results of Experiment 4c previously, this impairment is more evident in a normal reading condition, whereas when the inter-letter spacing is increased the deficit is less pronounced, because the overlapping of the integration fields of different letters is reduced in this latter case.

To summarize, in the present chapter, according to Martelli et al's dual model (2011), we integrated the previous findings on omission errors in ND (Primativo et al., 2013) by investigating the mechanisms underlying substitution errors. We demonstrated that, unlike omission-type ND, patients affected by substitution-type ND have preserved abilities to execute fine eye movements in both reading and non-reading tasks. Accordingly, specific training aimed at restoring the oculo-motor scanning was effective in reducing omission errors but did not improve reading in substitution-type ND. Conversely, patients with a prevalence of substitution errors showed an abnormal feature-integration process (i.e. crowding) that was reduced by increasing the inter-letter spacing. In accordance with previous studies (Bricolo et al., 2015; Paterson & Jordan, 2010; Bai et al., 2008), the inter-letter spacing manipulations affected not only reading performance but also eye-movement pattern during reading, with fewer and longer fixations in the normal spacing condition. Finally, we demonstrated that patients affected by substitution-type ND present a deficit in controlling attentional focus, and we suggest that this impairment is the underlying reason that causes the prevalence of substitution errors characterizing neglect dyslexia. Overall, the novelty of this study is the linking of the altered features integration process that causes substitution errors in ND to the impairment of control of focal component of spatial attention.

Chapter 6

General discussions

The series of experiments described in the present doctoral thesis demonstrates the dissociation of the focal and the orientation components of spatial attention in foveal and peripheral vision, and provides a novel account for substitution errors in neglect dyslexia.

In Chapter 2, through a set of four experiments, I described how the deployment of the focal component in foveal vision can be affected by the task demand and the stimuli used. The results of these four experiments highlighted that the focal component can be similarly elicited by different tasks (i.e. detection or discrimination) and by using different types of stimuli (i.e. shapes or letters). Furthermore, even if previous studies suggested that the temporal trend of the focal component includes both a primary period during which the attentional focus is exogenously controlled (e.g. Maringelli & Umiltà. 1998; Turatto et al., 2000), and a secondary period in which the focus of attention is endogenously maintained (e.g. Benso et al., 1998; Turatto et al., 2000), the analysis of the cue-size effect across the four experiments proved that the deployment of the focal component in foveal vision is best revealed and more effective under exogenous conditions.

In Chapter 3, through two experiments, I demonstrated that the focal and the orientation components of spatial attention operate independently in different viewing conditions and with different temporal trends. According to previous studies (e.g. Carrasco, 2011: Yeshurun & Carrasco, 1999; Yeshurun & Carrasco, 1998 Golla et al., 2004), orienting attention to a cued location enhances spatial resolution. However, the results here obtained from both a detection (Experiment 2a) and a discrimination task (Experiment 2b) suggested that focusing and orienting may operate independently. Specifically, the focal component does not modulate peripheral performance but rather dominates central vision, where the processing capacity is the highest, and is exogenously triggered, supporting the hypothesis of low efficiency of attentional focus when deployed outside the fovea (probably due to the poorer resolution of details in the peripheral part of the visual field). On the other side, the orientation component of spatial attention enhances peripheral processing time through largely, but not exclusively, endogenous control.

The results of Chapter 4 further extended the findings of Chapter 3 by demonstrating that the effects of the focal and the orientation components of spatial attention are dissociable not only in simple detection or discrimination tasks but also in a more demanding task that requires identifying a stimulus flanked by other stimuli. Previous studies already demonstrated that attention can reduce critical spacing (e.g. Felisberti & Zanker, 2005; Huckauf & Heller, 2002; Strasburger, 2005; Van der Lubbe & Keuss, 2001; Yeshurun & Rashal, 2010; Poder, 2007), by reducing the size of integration fields responsible for crowding. In addition, some authors have suggested that the crowding phenomenon reflects the limitation of the spatial resolution of attention (e.g. He, Cavanagh, & Intriligator, 1996, 1997; Intriligator & Cavanagh, 2001), although most of the literature on crowding suggests that it is a perceptual phenomenon linked to the features of neurons in the occipital cortex. Results from Chapter 4 confirmed the "attentional resolution" theory of crowding, demonstrating that directing attention to the target location can reduce the critical spacing at which distractors no longer interfere with the target stimulus. More interestingly, results from Chapter 4 proved that foveal (Experiment 3a) and peripheral (Experiment 3b) crowding are modulated independently by the two components of selective attention: the focal component is effective in suppressing crowding only in foveal vision, where processing capacity is the highest, whereas the orientation component reduces crowding only in peripheral vision, where the control of spatial position is the strongest.

Finally, in Chapter 5 I investigated the relationship between focal attention, crowding, and reading errors in patients with neglect dyslexia (ND). Those experiments allowed me to demonstrate the existence of a causal link between substitution errors and impairment in the control of focal component. Previous studies already showed that reading deficits in individuals with developmental dyslexia and posterior cortical atrophy (PCA) can be associated with a pathological crowding, which causes an abnormal integration of the letters presented simultaneously (e.g. Crutch & Warrington, 2007, 2009; Atkinson, 1991; Bouma & Legein, 1977; Spinelli et al., 2002), and that these patients' pathological crowding could be due to an alteration of the attentional mechanism (Mendez et al., 2007; Saffran & Coslett, 1996). In the matter of neglect dyslexia, a recent model by Martelli et al. (2011) proposed that the two most common reading errors in ND (i.e. omission and substitution errors) are due to different and independent mechanisms; whereas omission errors are due to a visuo-spatial mechanism responsible for omissions in both neglect dyslexia and unilateral spatial neglect, the substitution errors produced by neglect dyslexia patients in reading depend on the perceptual integration process that limits letter identification and is independent from USN, i.e. crowding. A recent study by Primativo et al. (2013) further demonstrated that omission errors in ND are the phenotypic expression of the interaction between the exploratory deficit of USN and an altered oculo-motor pattern, which prevents the automatic execution of the fine eye movements required for reading. Results from Chapter 5 integrated this investigation by demonstrating that almost all patients who show a predominance of substitution errors still have preserved abilities to execute fine eye movements in both reading and non-reading tasks, and that their reading impairment cannot be improved by a training program aimed at restoring normal oculo-motor behaviour. Conversely, patients with a prevalence of substitution errors showed an altered feature integration process (i.e. crowding) that can be reduced, both in terms of reading performance and eye-movement pattern, by increasing inter-letter spacing. Finally, I demonstrated that these patients are characterized by a deficit in the control of attentional focus in accordance with the task demands, in both exogenous and endogenous conditions. In particular, a deficit in the control of focal component would prevent the patient from "isolating" the letters from each other and separating the integration field of the single letters, therefore it would not allow them to correctly identify every signal, resulting in errors of misidentification.

Collectively, this evidence confirms the dissociation of the mechanisms underlying omission and substitution errors in ND and supports the specific role played by attention (and especially of the focal component of spatial attention) in reading and modulating crowding. Moreover, it suggests that such a dissociation could be extended to the effectiveness of rehabilitative procedures. In particular, patients who mainly omit letters would benefit from rehabilitation training directed at restoring normal eye movements, such as OKS, while patients who mainly substitute letters would benefit from rehabilitation training directed at the recovery of the ability to control and adjust the size of attentional focus.

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