Title
Location, Location, Fixation: Behavioral and Electrophysiological Explorations of Viewing Position Asymmetry in Visual Word Recognition

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Location, Location, Fixation: Behavioral and Electrophysiological Explorations of Viewing Position Asymmetry in Visual Word Recognition

A Dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

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by

Wen-Hsuan Chan

Committee in charge:

Professor Marta Kutas, Chair
Professor Virginia de Sa
Professor Steven Hillyard
Professor Roger Levy
Professor Douglas Nitz

2016

The Dissertation of Wen-Hsuan Chan is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2016

DEDICATION

To my father and my mother.

EPIGRAPH

別人離了象牙的塔走往十字街頭，我卻在十字街頭造起塔來住，未免似乎取巧罷？我本不是任何藝術家，沒有象牙或牛角的塔，自然是站在街頭的了，然而又有點怕累，怕擠，於是只好住在臨街的塔里，這是自然不過的事。只是在現今中國這種態度最不上算，大眾看見塔，便說這是智識階級，（就是罪，）紳士商賈見塔在路邊，便說這是黨人，（應取締。）不過這也沒有什妨害，還是如水竹村人所說「聽其自然」，不去管它好罷，反正這些閒話都靠不住也不會久的。老實說，這塔與街本來並非相干的東西，不問世事而縮入塔里原即是對於街頭的反動，出在街頭說道工作的人也仍有他們的塔，因爲他們自有其與大眾乖戾的理想。總之只有預備跟著街頭的眾去瞎撞胡混，不想依著自己的意見說一兩句話的人，才眞是沒有他的塔。所以我這塔也不只是我一個人有，不過這個名稱是由我替他所取的罷了。

— 周作人, 十字街頭的塔

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W-H Chan, T. P. Urbach & M. Kutas (2015). Look here: An event-related brain potential (ERP) investigation of the optimal viewing position (OVP) in word recognition. *The 22nd annual meeting of Cognitive Neuroscience Society (CNS)*, San Francisco, USA

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ABSTRACT OF THE DISSERTATION

Location, Location, Fixation: Behavioral and Electrophysiological Explorations of Viewing Position Asymmetry in Visual Word Recognition

by

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Doctor of Philosophy in Cognitive Science

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Professor Marta Kutas, Chair

Where a reader's eyes fixate within a word influences how accurately and quickly a word is recognized. Mapping performance against fixation within a word gives the "viewing position (VP) curve," which has an inverted-U shape with better recognition at word beginning than end and best recognition at a fixation slightly left-of-center (optimal viewing position, OVP). There are data supporting each of the major, non-mutually exclusive accounts of these VP asymmetries: informativeness, cerebral laterality, and perceptual learning. However, none of them can explain why reverse VP asymmetries have not been observed. It is my thesis that these issues are in large part because stimulus and reader characteristics both are critical in visual word recognition. We addressed the issues by using a target discrimination task in a VP paradigm for a variety of more-or-less word-like strings. Behavioral results show (1) all strings yield an U-shaped VP curve; (2) all but strings with no letter-like features show a beginning-vs-end VP asymmetry, ruling out an account based wholly on either informativeness or left cerebral specialization for word processing; (3) only words exhibit a left-to-center OVP, suggesting cerebral laterality and/or informativeness may play a role; (4) perceptual learning also falls short of explaining the deleterious effect on performance of the number of characters in the target's VF (i.e., visual crowding). Using event-related potentials, our investigation on the neural mechanisms of the VP effects find (1) the continuity of fovea to parafoveal processing assumption, required for the cerebral laterality account, however, interacts with VF, and (2) an electrophysiological index of the OVP effect in the early sensory P1 component. Compared to prior research, we use a broader range of stimulus types, at more locations in visual space, in a target discrimination task, thereby affording a not only finer-grained analysis of the VP curve but also filling significant empirical gaps. For the first time, we dissociate the beginning-vs-end and OVP asymmetries, and further uncover an important role for an unexamined factor: visual crowding. Moreover, by filling these empirical gaps, we provide additional constraints on any empirically adequate account and conclude that no current alternative is wholly satisfactory.

Chapter 1

General Introduction and Background

"Raednig thees wrods semes to be esaeir tahn you mgiht hvae tohuhgt; waht colud epxlian tihs?"

— *Shillcock*

Although there is clearly something amiss with the sentence above, readers have no trouble recognizing these words and understanding their meaning. However, this is counterintuitive: if we read words based on their written forms, as linguistic textbooks suggest that we do, analyzing words to extract information about their phonology and semantics, then how is it possible we are able to read such a sentence? Our ability to do so brings into question just what our understanding of written word recognition is.

At minimum, there are two distinct components of written word recognition: the words and the readers who read and make sense of them. Psychologists, linguists, and psycholinguists have paid considerable attention to the words themselves, asking questions like what makes a word a word? What are formal structures of words? What kinds of human behaviors reveal the properties and linguistic structure of words? Focusing on word properties and how they influence human performance would seem to offer a solid basis for understanding word recognition. On this approach, however, human word recognition behavior is just evidence for or against formal linguistic principles, rather than a means for understanding word recognition processes. McDonald, Carpenter, and Shillcock (2005) writes:

> *"Historically, the development of processing accounts of reading has been driven predominantly by psycholinguistics, with principal theoretical categories – lexis, syntax, semantics – being drawn from formal linguistics."*

Our ability to understand the introductory sentence above is problematic for theoretical frameworks on which word recognition processes unfold in this classical way. However, I think that word recognition is neither a process involving only the linguistic elements of words nor merely a mapping of linguistic principles onto the human brain. It is my thesis that word recognition is also a cognitive process – a computational process, or set of processes that takes place in human brain, subject to its anatomy and functional organization that is modified by our experience.

If we view written word recognition as a visual process conducted by the human visual system, then it follows that we can better understand word recognition by taking into account what is known about human visual perception, its anatomy and its functional organization. For example, Wertheim (1894) found that there is a sixty percent reduction in visual acuity at an eccentricity of one degree from fixation. As a consequence, we see something clearly near fixation and something less clearly as it gets farther from fixation. Since words have to be seen to be read, one might suppose the rapid drop-off of visual acuity from fixation is a critical limiting factor on visual word recognition. To better understand word recognition, then, it would seem important to consider the constraints on visual perception. Given acuity constraints on perception, where readers fixate within a word could be critical for word recognition: some fixations might be better than others.

Intuitively, we might assume that the center of a word is the best viewing position, perhaps because we suppose, right or wrong, that it allows us to see the entire word. To test this hypothesis, J. O'Regan, Lévy-Schoen, Pynte, and Brugaillère (1984) systematically manipulated participants' initial fixation position by displaying words horizontally shifted relative to fixation. Surprisingly, a word' s center was not the best fixation position. The speed and accuracy of recognition were respectively faster and higher the closer the eye's initial fixation was to a point slightly to the left of center of the fixated word. This phenomenon is known as the optimal viewing position (OVP) effect.

The left-of-center asymmetric OVP pattern shows that word recognition depends on viewing position, and is prima facie evidence that word recognition is influenced not only by word properties, but also by constraints on the human visual perception system. My dissertation research – with the ultimate aim of better understanding word recognition – will focus on the viewing position (VP) curve of which the left of center OVP is one important feature, as well as some of the major factors that likely may contribute to it, including the human visual system, hemispheric specialization for language, low-level statistical properties of words, and the shaping of visual perception by language experience.

1.1 The Viewing position (VP) curve and the VP effects

Performance on visual word recognition varies as a function of where the eyes initially fixate within a word. Mapping performance against fixation location within a word gives the so-called “viewing position (VP) curve” which generally has three salient characteristics. First, the overall shape of the VP curve is an inverted U: performance declines as the eyes fixate toward either edge of a word. Second, this performance drop is larger for fixations at the word’s end letters than at its beginning letters, such that the VP curve is asymmetric. Third, the fixation location that leads to the best performance, the so-called the optimal viewing position (OVP) is left-of-center within the word. These three characteristics or VP effects, namely, (1) the inverted U-shape, (2) lower recognition performance for fixations at the end vs. beginning of words, and (3) the left-of-center OVP, are well-attested in both isolated visual word recognition tasks (J. O’Regan et al., 1984) and in reading (Vitu, McConkie, Kerr, & O’Regan, 2001). These effects are reliably observed across a variety of tasks, including word naming (Brysbaert, 1994), lexical decision (Brysbaert, 1992), and perceptual identification (Stevens & Grainger, 2003). Investigations of VP effects are an important and arguably essential means of studying visual word recognition.

1.2 Why study VP effects as a means of better understanding visual word recognition?

For one, the left-of-center OVP reveals the way that readers naturally fixate words – and yet most laboratory studies of visual word recognition present words either centered at fixation or lateralized approximately 2 degrees in the parafovea. Theories of visual word recognition need to be able to account for the data patterns regardless of the presentation format. To the extent that hemispheric differences for language processing impact the functioning of the human cognitive system, it would seem some consideration need be directed at processing in the fovea and its role in generating asymmetric effects (VP and otherwise). Last but not least, at minimum the study of VP effects provides invaluable empirical observations on how letter position relative to fixation and/or other letters within the word modulates human performance on visual word recognition (J. O'Regan & Jacobs, 1992). Such data are essential to any descriptive or computational model of word recognition, which I think must ultimately code for letter position and explain letter position effects on word processing (Grainger, 2008; Lavidor & Walsh, 2004; C. Whitney, 2001; C. Whitney & Lavidor, 2004; C. Whitney & Cornelissen, 2005; C. Whitney, 2004).

Using the VP curve as a means of investigating word recognition accords well with trends in recent research, where focus had shifted away from integration across abstract domains of representation (orthography, phonology, semantics) to the front-end (lower level) of visual word recognition processes (e.g., foveal representation) (Grainger, 2008; Lavidor & Walsh, 2004; C. Whitney, 2001; C. Whitney & Lavidor, 2004; C. Whitney & Cornelissen, 2005; C. Whitney, 2004). Indeed, VP effects are taken as evidence of the split fovea theory of foveal representation. According to split fovea theory, any asymmetries around the fovea suggest that partial word information on either side of fixation has consequences for visual word recognition. The two asymmetric VP effects, thus, can be used to examine how partial word information (which initially projects to the contralateral hemisphere) reunites via inter-hemispheric transfer, integration, and as a function of hemispheric specialization (Brysbaert, 2004, 1994, 1992; Brysbaert & Nazir, 2005; Hunter & Brysbaert, 2008).

This dissertation investigates the nature and underlying mechanisms leading to the VP curve and associated VP effects, with the ultimate aim of better understanding visual word recognition.

1.3 Theoretical Accounts for the Viewing Position Effects

Many theories have been proposed to account for the three VP effects described above. There is a general consensus that VP curve's overall inverted U-shape is attributable to decreased visual acuity as a function of stimulus eccentricity from fixation (J. O'Regan & Jacobs, 1992; McConkie, Kerr, Reddix, & Zola, 1988; J. K. O'Regan, 1989; Nazir, 1991; Nazir, Jacobs, & O'Regan, 1998). Since visual acuity drops off drastically even within the fovea (Levi, Klein, & Aitsebaomo, 1985; Olzak & Thomas, 1986; Nazir, Heller, & Sussmann, 1992), the quality of visual information is maximal at fixation. For a fixation at around a word's center, average acuity over letters is larger than that for a fixation at the extreme letters of a word. The inverted U shape generally reflects the average quality of visual information while moving fixation along the letter positions in a word (J. O'Regan et al., 1984). On this view, the inverted U-shaped VP curve is a consequence of a general property of the human visual system and not specific to visual word recognition. It should thus be observed for any and all visual stimulus strings. I will test this prediction by using a variety of different stimulus strings in this dissertation.

By contrast, there is considerable theoretical debate – i.e., no general consensus – regarding the mechanism(s) responsible for the beginning vs end asymmetry of the VP curve and the center-to-left OVP asymmetry or both. To our knowledge, no single theory provides a complete account for these two asymmetries.

There are three main accounts for the first vs last asymmetry of the VP curve: (1) the cerebral laterality account, (2) the perceptual learning account, and (3) the informativeness account. These three accounts offer very different mechanisms for explaining the asymmetry of the VP effect. They provide different, albeit not mutually exclusive, explanations of how the asymmetry of VP effects arise from perceptuo-cognitive factors that contribute to visual word recognition: (1) the functional organization of the brain (in the case of the cerebral laterality account), (2) experience-dependent processing (in the case of the perceptual learning account), and (3) the structure of stimulus properties (in the case of the informativeness account). As there are supporting data for each of these accounts – at least with respect to the beginning vs end VP asymmetry, and no general consensus for any one of them – this dissertation aims to collect discriminative data that will allow to better access these accounts.

1.3.1 The cerebral laterality account

On the cerebral laterality account, the beginning vs end VP effect asymmetry is due to left hemispheric specialization for word processing (Brysbaert, Vitu, & Schroyens, 1996; Brysbaert, 1994). Specifically, partial word information on each side of fixation projects to the contralateral hemisphere: letters to the left of fixation directly project to the right hemisphere (RH), and letters to the right of fixation directly project to the left hemisphere (LH). On this account, word processing can begin only after information concerning the entire word has been transferred to the LH (Haegen & Brysbaert, 2011; Haegen, Brysbaert, & Davis, 2009; McCormick, Davis, & Brysbaert, 2010; C. Whitney, 2001). Transfer time cost depends on the amount of information that must be transferred serially (Brysbaert, 1994). As a consequence, there is a greater processing cost for fixations at the final letters of a word since all letters are initially projected via the left visual field to the RH; in contrast, fixations at the initial letters of a word require either little or no inter-hemispheric transfer from the right visual field to the LH (Haegen & Brysbaert, 2011; Haegen et al., 2009; McCormick et al., 2010; C. Whitney, 2001).

The cerebral laterality account aims to explain the beginning vs end VP asymmetry based on the relative inter-hemispheric time cost among fixation locations due to the transfer of word information from the right to the left hemisphere. Given that the left hemisphere is specialized for word processing (compared to the right), fixations to a word's beginning benefit from this brain organization whereas fixation to a word's end do not. The cerebral laterality account, however, does not offer any explicit explanation of the (asymmetric) OVP.

1.3.2 The perceptual learning account

The perceptual learning account proposes that the asymmetric VP curve – both the beginning-end VP asymmetry and the OVP asymmetry – arises via the shaping of processing preferences in visual space by extensive reading experience – i.e., by perceptual learning. The essence of this account is based on Mishkin and Forgays (1952) hypothesis that reading habits modify the way readers perceive print. On the perceptual account, reading does not perceptually train all parts of the retina equally and the more training that a part of the retina receives, the better that part processes (Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004). Specifically, the perceptual learning account relies on two canonical eye movement patterns in reading to explain the asymmetric VP effects: namely, the distribution of eye landing positions within a word and reading direction (Nazir et al., 2004; Nazir & Huckauf, 2008; Nazir, 1993). When reading (at least English), the eyes land more frequently on the initial letters of a word than on its final letters; this is known as the preferred landing position (PLP) (Vitu, O'Regan, & Mittau, 1990; Rayner, 1979). The perceptual account proposes that the PLP provides frequent retinal training for processing initial letters compared to those at a word's end. Similarly, reading direction perceptually trains and thereby favors parts of retina on the side in the reading direction (Nazir et al., 2004). For example, reading a left-to-right language (such as English) may perceptually train the right visual field (RVF) more than the left visual field (LVF), and this is manifest in superior visual word recognition in the RVF relative to the LVF.

According to the perceptual learning account, it is this differential perceptual training of the retina that results in the observed perceptual asymmetry between the two visual fields. The drop-off in the visual acuity function becomes asymmetric between the LVF and the RVF (Nazir, O'Regan, & Jacobs, 1991; Nazir et al., 1992). And, for a left-to-right language such as English, the visual acuity drop-off is steeper in the LVF than in the RVF. The letters of a word that span across retinal locations to the left and right of fixation thus are processed better or worse depending on which visual field they fall and where they are relative to fixation. Words are better recognized at a fixation where all the individual letters are well recognized than when some letters are positioned at disfavored retinal locations. As fixating the beginning of a word positions the majority of letters in the RVF and fixating the end of a word positions the majority of letters in the LVF, this visual field asymmetry is the presumed basis for the beginning vs end asymmetric VP effect. Based on the same logic, computing the overall perceptibility at various fixations leads to an asymmetric OVP effect. Assuming visual acuity decreases more rapidly in the LVF than in the RVF, a maximized average visual acuity (quality) over letters would be at a left-to-word center fixation. In sum, the perceptual learning account relies on perceptual learning from reading experience to yield a left-right visual field asymmetry, which in turn explains both the beginning vs end asymmetric VP effect and the asymmetric OVP effect.

1.3.3 The informativeness account

The informativeness account of the beginning vs end asymmetric VP effect relies on the differential information distribution across the letter positions within a word for a given language – i.e., the linguistic knowledge of orthographic written forms in a language (Holmes & O'Regan, 1987; J. K. O'Regan & Lévy-Schoen, 1987;

J. O'Regan & Jacobs, 1992; J. O'Regan et al., 1984; Clark & O'Regan, 1999; Brysbaert et al., 1996; Stevens & Grainger, 2003; Pynte, Kennedy, & Murray, 1991; Farid & Grainger, 1996). Taken to its conclusion, the informativeness account predicts that words (or languages) with different information distributions would yield different VP curves. The shape of the VP curve is taken to directly represent the informativeness distribution (Clark & O'Regan, 1999; Legge, Klitz, & Tjan, 1997).

It has been suggested that, at least in some languages such as English, words' initial letters carry more information about word identity than final letters. According to the informativeness account, this trend is exactly captured in the beginning versus end asymmetric VP effect. The processing benefit observed for fixations at the beginning versus end of a word is taken to reflect the greater informativeness of word-initial versus word-final letters. Support for this account comes from research showing that varying the locus of informativeness modulates the morphology of the VP curve and various VP effects as expected: e.g., for words carrying more information in word-final letters, the beginning vs end asymmetry diminishes, and the OVP moves toward the center of a word. Moreover, large-scale corpus analyses demonstrate that the distribution of information within words is similar to the observed VP curve. The (hypothetical modeled) VP curve based on the informativeness distribution appears to demonstrate all three VP effects: (1) the inverted U-shaped VP curve, (2) the beginning-end asymmetric VP curve, and (3) the asymmetric OVP.

1.4 Disentangling the factors that contribute to the asymmetric VP effects

As already noted, despite the fact that these are fundamentally different accounts of the beginning vs end asymmetric VP effect, each has garnered data in line with its predictions. For example, consistent with the cerebral laterality account, the beginning vs end asymmetric VP effect is smaller for the individuals with right (than left) hemispheric specialization for word processing (Brysbaert, 1994; Brysbaert et al., 1996; Hunter & Brysbaert, 2008). Consistent with the perceptual learning account, the VP curve is modulated by reading direction: for readers of a right-to-left language such as Arabic, the VP curve is relatively more symmetric in both the beginning vs end difference and the locus of the OVP (Farid & Grainger, 1996; Nazir et al., 2004). Consistent with the informativeness account, the VP curve for words with high-informativeness at their ends (rather than beginnings) is comparatively more symmetric than the typically asymmetric curve (Brysbaert et al., 1996; J. O'Regan et al., 1984). However, in no case have reversed asymmetric VP effects for either the word beginning vs end asymmetry or the OVP asymmetry been observed (or at least reported) in human performance data. And yet, an end vs beginning VP asymmetry is predicted by the cerebral laterality account for individuals with right hemisphere specialization for word processing, by the perceptual learning account for individuals with a right-to-left reading direction, and by the informativeness account when more information is word-final. From a theoretical perspective, this suggests that none of the extant accounts can fully explain either or both of the asymmetric VP effects. Moreover, from a methodological perspective, this raises the possibility that the factors contributing to the asymmetric VP effects are confounded and need to be teased apart.

1.4.1 Using word stimuli leads to confounds

I am of the opinion that the difficulty of disentangling the various contributory factors to the two asymmetric VP effects stems from the fact that stimulus characteristics (e.g., informativeness and perceptual learning) and reader characteristics (e.g., cerebral laterality and perceptual learning) are both critical in determining visual word recognition. Fixating at a word's end positions the word in the LVF whereas fixating at a word's beginning positions the word in the RVF. Informativeness and visual field are confounded. Disentangling the contributions of word beginnings (with high informativeness) from the potential benefits accruing from the majority of letters being in the RVF (due to left hemisphere specialization for word processing or greater visibility resulted from perceptual learning) to asymmetric VP effects is impossible. Furthermore, even when word properties are controlled, it is difficult to distinguish the role of the right visual field in the cerebral laterality account from that in the perceptual learning account. Specifically, with respect to the asymmetric VP curve effects for words, it is difficult to disentangle the processing benefits for letters in the RVF due to asymmetric tuning of visual acuity as suggested by the perceptual learning account or left hemispheric specialization for word processing as suggested by the cerebral laterality account.

What are options other than words?

As the investigations on the VP curve center upon language processing, words are traditional stimuli used to examine factors that contribute to the asymmetric VP effects. However, as I pointed out, using words as stimuli leads to inevitable confounds due to the nature that word characteristics interact with reader characteristics. In my opinion, a feasible alternative to disentangle the factors that contribute to the asymmetric VP effects is to examine the VP effects for visual stimuli that are not necessary words. Traditionally, manipulations on "nonwords" commonly operate on manipulations of letter combinations that lead to various degrees of orthographic or phonological correspondence compared to real words. However, "not word stimuli" that I propose here will instead be the stimuli that may or may not contain letter or letter-like features which will push the scope of investigations beyond language processing *per se*. By setting back stimulus characteristics from words, the observed versus absent VP effects will allow us to isolate the factors that contribute to the VP effects of stimulus characteristics from reader characteristics. Moreover, as the VP effects are commonly discussed as word phenomena, a critical but ignorant position - whether the VP effects are word-specific - could be explicitly examined by using more or less word-like strings. Indeed, three major accounts for the VP effects predict different levels of word-specificity for the VP asymmetries. With respect to the cerebral laterality account on LH specialization for word processing, VP asymmetries should be restricted to words. While the perceptual learning account addresses location-specific and stimulus-specific perceptual learning mechanisms during acquisition of reading skills, the presence of VP asymmetries requires processing for stimuli that contain letters or letter-like features. Although the informativeness account on a statistical distribution over a stimulus string is developed for lexical knowledge, it may predict VP asymmetries for the stimulus regardless of whether or not the stimulus is a word as long as the stimulus string carries an asymmetric informativeness distribution that is learned by an individual. Consequently, such manipulations on stimulus characteristics with various more or less word-like strings will provide insights on the extent to which language related processing plays a role on the VP effects.

Relevance of visual perception factors to the study of VP effects

An issue that will be raised immediately along this approach using general visual stimulus is whether relevant components of visual perception should be considered with respect to their potential contributions to the VP effects. One such component, visual acuity, has been included in a discussion of the VP effects: (a) a general consensus for an U-shaped VP curve and, (b) an asymmetric visual acuity function between the two visual fields that the perceptual learning account takes to account for the VP asymmetries. Visual crowding, which is intensively investigated in the literature of visual perception (D. Whitney & Levi, 2011), however, seems to be omitted in a discussion of VP effects. As visual crowding refers to an impairment of recognition due to a target's surrounding objects, visual crowding has been suggested as an essential bottleneck of object perception (Levi, 2008). Visual word recognition, indeed, is a type of recognition that involves overcomes/interactions with visual crowding in highly visual crowded situations as we know that visual word recognition depends on the ability of successful letter recognition (Pelli, Farell, & Moore, 2003; Pelli et al., 2007).

In my opinion, there are two main reasons that visual crowding has not been included in a discussion of the VP asymmetries, one theoretical and one methodological. First, as I pointed it out in the earlier paragraph, word characteristics that have been mapped onto theoretical (linguistic) principle categories are overemphasized compared to reader characteristics. The attention on word processing is historically skewed toward treating written words as linguistic objects instead of visual objects as well. Second, as by definition that the VP curve is a function of recognition performance relative to fixation within a word, tasks such as lexical decision or naming tasks that are used to measure recognition performance usually depends on a single response to a whole word. Given the nature of tasks, with a single response to a fixed number of letters within a word, it is limited for the examinations on performance impacted by visual crowding. Given this, potential contributions of visual crowding could be drawn, at most, from better recognition performance for fixations at the extreme letters (first or last letter of a word) due to a partial release of visual crowding for an absence of adjacent letter at these two extreme letter positions. However, the potential contributions of visual crowding inferred through these comparisons between fixations at the extreme versus the rest of letter positions are confounded with the contributions of visual acuity. Fixating at the extreme letter positions also lead to an averagely lower visual acuity over an entire word as it has been suggested as a foundation of an U-shaped VP curve.

I am of an opinion that a shift of attention to “not word stimuli” for the investigations of VP effects, in fact, will naturally lead to a possibility to address visual crowding properly due to its need of using tasks other than those depend on a single response to a whole word. One of tasks that has been used to examine contributions of visual acuity to the VP asymmetries with letter strings is a target letter discrimination task - one target letter embedded at a random letter position in a letter string

Furthermore, an assessment on factors of visual perception - both visual acuity and visual crowding will provide critical information for teasing apart contributions of VP effects from mechanisms proposed by three major accounts - cerebral laterality, perceptual learning, and informativeness. For both the cerebral laterality and informativeness accounts, the mechanisms that come into play to contribute VP effects begin by assuming the availability of visual information - either the inter-hemispheric transfer delay for abstract letters from the RH to the LH or a statistical computation on abstract letter (character) identities. Factors of visual perception, therefore, play a minimal role on these two accounts. On the other hand, the perceptual learning account is based on the idea that perceptual learning may modulate visual perception, which leads to constraints of the availability of visual information in the human visual system and brain. Without addressing a role of visual crowding, however, imposes difficulties to evaluate the proposed mechanisms of the perceptual learning account to the VP effects and the role of visual perception in a scenario of visual word recognition. Experimental designs - such as a target discrimination task combined with the viewing position paradigm - that allows to better assess visual acuity and visual crowding, therefore, will provide critical information for both better understanding the roles of mechanisms proposed by the three major VP accounts and visual word recognition in general.

1.4.2 The temporal dynamics of the asymmetric VP effects may help distinguish the three major accounts

Let's revisit the three main accounts for the asymmetric VP effects. On the cerebral laterality account, the asymmetric VP effects reflect a need to transfer partial word information from the RH to the LH; (2) on the perceptual learning account, the asymmetric VP effects arise from asymmetric perceptual tuning of visual inputs; and (3) on the informativeness account, the asymmetric VP effects reflect an asymmetric distribution of lexical information over the letter positions within a word, We have already discussed how these proposed mechanisms differ in their dependence on word processing *per se*, such that we can tease apart these mechanisms (factors) by comparing the VP curves for more or less word-like stimuli, as well as by examining the contributions of visual factor such as visual acuity and visual crowding.

Another effective approach to teasing apart these alternative accounts is to delineate the temporal dynamics of processes hypothesized to contribute to the asymmetric VP effects, as they presumably act at different times. Viewed from a purely bottom-up perspective, the contribution of perceptual learning mechanisms precedes that of informativeness, which in precedes that of cerebral laterality, as the stimulus progresses from early to late stages of processing. Although the exact temporal order of engaged mechanisms may differ if top-down feedback mechanisms are also taken, my point is that the temporal dynamics of the asymmetric VP effects could prove to be a critical dimension that for evaluating the proposed mechanisms and their relationships. The observed asymmetric VP effects for words are based on behavioral measures that reflect the combined outcomes these multiple stages of processing. If, however, our ultimate goal is to understand how the asymmetric VP effects come to be and the roles they play in visual word recognition, we need tools for tracking the time course of processing and the responsible functional brain mechanisms, reflected in the asymmetric VP effects.

Indeed, this is viable means of distinguishing and assessing the alternative accounts as they rely on different assumptions about the brain. The proposed mechanisms of the cerebral laterality account, for example, are based on certain assumptions about foveal representations for word processing. The perceptual learning account, on the other hand, taken together with general theories of perceptual learning, implicate perceptual tuning changes in early visual areas for language-relevant visual objects.

Conventional measurements of recognition performance, such as recognition accuracy and reaction times do not have the resolution to track the time course of the VP effects with sufficient resolution. By contrast, event-related brain potentials (ERPs) do. I thus plan to utilize event-related brain potentials (ERPs), following in the footsteps of several researchers of these sorts of issues (Martin, Nazir, Thierry, Paulignan, & Démonet, 2006; Martin, Thierry, Démonet, Roberts, & Nazir, 2007; Rosazza, Cai, Minati, Paulignan, & Nazir, 2009; Jordan, Fuggetta, Paterson, Kurtev, & Xu, 2011).

I propose to employ the ERP methodology to better identify the functional mechanisms leading to the behavioral VP effects. First, I will use ERPs to examine assumptions about the nature of foveal representation and its relation to the visual fields on which the cerebral laterality account is based. By focusing on foveal representation I will also begin to collate a base of electrophysiological phenomena of visual recognition in the viewing position paradigm. Furthermore, I aim to find (an) electrophysiological index(es) of asymmetric VP effects, which to my knowledge has not yet been reported in the literature. Such a finding would not only complement the behavioral data but also help to winnow down the viable theoretical accounts for VP effects and their role in visual word recognition.

1.5 Primary questions of thesis

This thesis aims to establish the nature and scope of the asymmetric VP effects – beginning vs end and OVP - and to isolate the specific contributions of the various factors proposed by the different theoretical accounts. We focus primarily on the cerebral laterality and the perceptual learning accounts for the two asymmetric VP effects in particular.

Very few studies of the VP curve have examined non-word strings, and even the few who have used only a limited number of locations: fixation either at word end or beginning (i.e., wholly in the LVF or RVF, respectively), or at word's center, and very rarely both in the same experiment. Nor have these studies examined intermediate fixation positions within a string, which leads to different numbers of letters in the two visual fields. The reported VP curves thus are routinely extrapolated from the two or three string positions typically used. I believe more fixation positions are essential to more precisely delineate the curve. Accordingly, in Experiment 1 (Chapter 2) I do both: I examine all three features of the VP curve for (non-word) letter strings in both visual fields and spanning central fixation. In so doing, the results of this experiment will allow us to adjudicate between cerebral laterality and perceptual learning as the sole account for the beginning vs end VP asymmetry and the left-of-center-OVP. According to the cerebral laterality account, both asymmetric VP effects are a consequence of left hemisphere specialization for word processing. Thus VP curves for non-word letter strings should not present with either the beginning vs end asymmetry or the left of center OVP asymmetry. To the extent that they do – even though word level processing has been eliminated – we can rule out an account based solely on left hemisphere processing for words (i.e., the cerebral laterality account). If, by contrast, either or both asymmetric effects are absent, then we could entertain the hypothesis that that asymmetric VP effect might be word-specific.

For non-word letter strings, we find the general inverted U-shape and the beginning vs end asymmetric VP effect but not the left-of-center OVP asymmetry. The presence of the beginning versus end VP asymmetry for non-word letter strings means that this asymmetry is not word specific and that invoking left hemisphere specialization for word processing is not necessary to account for it. Moreover, our analysis shows that the beginning vs end asymmetric VP effect is consistent with better performance in the RVF than in the LVF, and with the view that perceptual asymmetry may mediate the asymmetric VP effects.

Since these data indicate that a perceptual learning account suffices to explain at least the beginning vs end VP asymmetry, in Chapters 3 and 4, we look more closely at the perceptual learning account. In Chapter 3 we examine the scope and generality of the characteristics of the VP curve in two experiments, by varying the nature of the characters of the visual stimulus strings – namely, letter-like symbol strings in Experiment 2 and strings of broken rings that are not distinguishable by letter-like features in Experiment 3.

According to the perceptual learning account, both the asymmetric VP effects arise from perceptual training during reading. As such these effects should be specific to print – presumably letters or letter features. If so, we expect to observe the beginning vs end asymmetric VP effect to strings of symbols which contain letter-like features (Experiment 2) but not to those that do not (Experiment 3). As that is the pattern of results that we observe, in Chapter 4, we critically examine an explicit model of the perceptual learning account of the asymmetric VP curve effects, namely the Multiplied Identification Processing (MLIP) model. The MLIP was developed to show that the VP curve asymmetries could arise from a perceptual asymmetry due to a differential drop-off in visual acuity between the two visual fields (steeper in the LVF than RVF). I would like to argue, however, that the drop-off in visual acuity may not be the only factor contributing to the perceptual asymmetry and thus to the asymmetric VP effects. I would like to make a case that visual crowding asymmetries between the two visual fields also contribute to the perceptual asymmetries and thus to at least the beginning vs end asymmetric VP effect. Crowding is a visual phenomenon referring to an impairment of recognition due to its surrounding objects.

My argument is based on an appreciation of the relationship between the VP curve and general visual recognition patterns. The VP curve, by definition, is a function of recognition performance relative to fixation within a word. For example, given a five letter word, the region of interest for VP effects is within the area spanning fixation (See Figure 1.1). As mentioned above, we routinely test all five string positions, whereas the perceptual learning theorists have only tested string positions 1 and 5, or 3 (which is also used to investigate the perceptual span) for non-word letter strings. This focal VP area, however, is a subset of the observer's larger visual field (as in Figure 1.2). Research on visual recognition in general thus subsumes the VP region, but goes beyond it (See Figure 1.2). Although the stimuli and/or tasks used in studies of visual recognition are not specifically designed to examine the various asymmetric VP effects, there is, as of yet, no principled reason to assume that the VP curve is not subject to the same factors as visual recognition more generally.

As for the various VP effects, visual acuity plays a similar important role in accounts of the recognition asymmetry for letter strings in the two visual fields. In addition, it has been shown that visual crowding likewise plays an important role on visual recognition patterns, especially for the asymmetric recognition patterns between the two visual fields. We can reasonably ask whether visual crowding contributes to the beginning vs end VP asymmetry and should be incorporated into the MLIP model. We can examine visual crowding only if we do not collapse recognition scores across letter positions within a string at a given fixation, as is typically done for VP curve calculations. In Chapter 4, we thus re-analyze the data from Experiments 1, 2, and 3, keeping recognition for each letter as a function of its relative location within a string and relative to fixation.

Our re-analysis indicates that both visual acuity and crowding contribute to the VP curve effects overall. However, visual crowding asymmetry between the two visual fields (larger in the LVF than RVF) suffices to explain the beginning vs end VP asymmetry for non-word letter strings and non-letter symbols. The absence of an asymmetry in visual crowding for the non-linguistic (broken ring) sequences likewise mirrors the symmetry of the beginning vs end VP effect. This pattern of results suggests that perceptual learning during reading may shape perceptual asymmetry in crowding, which is reflected in the asymmetry of the VP curve.

Since this is a novel proposal/explanation for the beginning vs end VP curve asymmetry, in Chapter 4 we replicate Experiments 1 (nonword letters), 2 (non-letter symbol strings), and 3 (nonlinguistic ring strings) in a within subject design, essentially replicating the main findings as well. While we observed the beginning vs end asymmetric VP effect for all but non-letter ring strings, we did not observe the left-of-center OVP asymmetry for any of the stimulus strings. Thus, in Chapter 5 we examine the characteristics of the VP curve for words, known to elicit the asymmetric OVP and for pseudowords, where the OVP results are mixed. We used the letter discrimination task that provides a richness of performance data – in letter recognition at each fixation position and letter position within a string (word and pseudoword) – so that we could examine potential visual field differences in letter recognition and crowding asymmetry between the two visual fields, and thus assess the perceptual learning account. We created stimuli for which several critical lexical properties (neighborhood frequency and bigram frequency) over target positions and target letters were controlled. And, since the sublexical factors were matched across words and pseudowords, we could use recognition differences between them to determine which, if any VP effects, were specific to words. Our results indicate that the left-of center OVP might be word specific, which offers some limitations on a perceptual learning account of the beginning vs end VP asymmetry based solely on a crowding asymmetry between the visual fields. We observe no visual crowding asymmetry for words, although there is a visual acuity asymmetry across the fields.

In Chapter 6, we record event-related brain potentials (ERPs) to lateralized non-word letter strings flashed in the foveal or the parafoveal regions. A letter discrimination task within a viewing position paradigm is used in order to assess continuity of processing across the visual field. According to the cerebral laterality account, the RVF advantage for parafoveal words and the word beginning vs end asymmetric VP effect for foveal words both have the same neural basis — left hemisphere (LH) dominance for language. We test this proposal by measuring the amplitudes and latencies of early visual evoked potentials (occipital P1 and N190), both ipsilateral and contralateral to the side of stimulus presentation. We then use these, following the literature, to calculate interhemispheric transfer times and amplitude reductions. We find inter-hemispheric transfer times are faster for RH-to-LH transfer than LH-to-RH transfer, consistent with better behavioral performance for stimuli to the right than left side of fixation, foveally and parafoveally. Although the occipital N190 to lateralized stimuli in the fovea was generally shorter in latency and larger in amplitude than for stimuli outside the fovea, these differences were larger in the RVF than LVF. This pattern of results cannot be explained by a processing continuity assumption if LH specialization for language is the responsible mechanism. Moreover, we also found larger amplitude reductions for transfer from the RH-to-LH than vice versa, further implicating contributing factors other than left hemisphere dominance for language in the observed hemispheric differences.

Because we observed the center-to-left OVP for words only, in Chapter 7, we used the ERP technique to begin to understand the neural mechanism of this word-specific effect. Specifically, we recorded ERPs to words and nonwords presented foveally at two different within-string fixation locations – namely, at the OVP (slightly left of string center) and at the string's center. We expected this fixation manipulation to impact word processing but not nonword processing. Although occipital P100 amplitudes were larger for longer strings than shorter strings, regardless of lexical status and fixation, only words showed an effect of fixation position. P100 amplitudes over right occipital sites were smaller for words positioned at the OVP than at the word's center; this P100 amplitude difference between fixations is negatively correlated with word length. This pattern of effects leads us to suggest that location normalization for invariance during visual word recognition may occur around 100 ms.

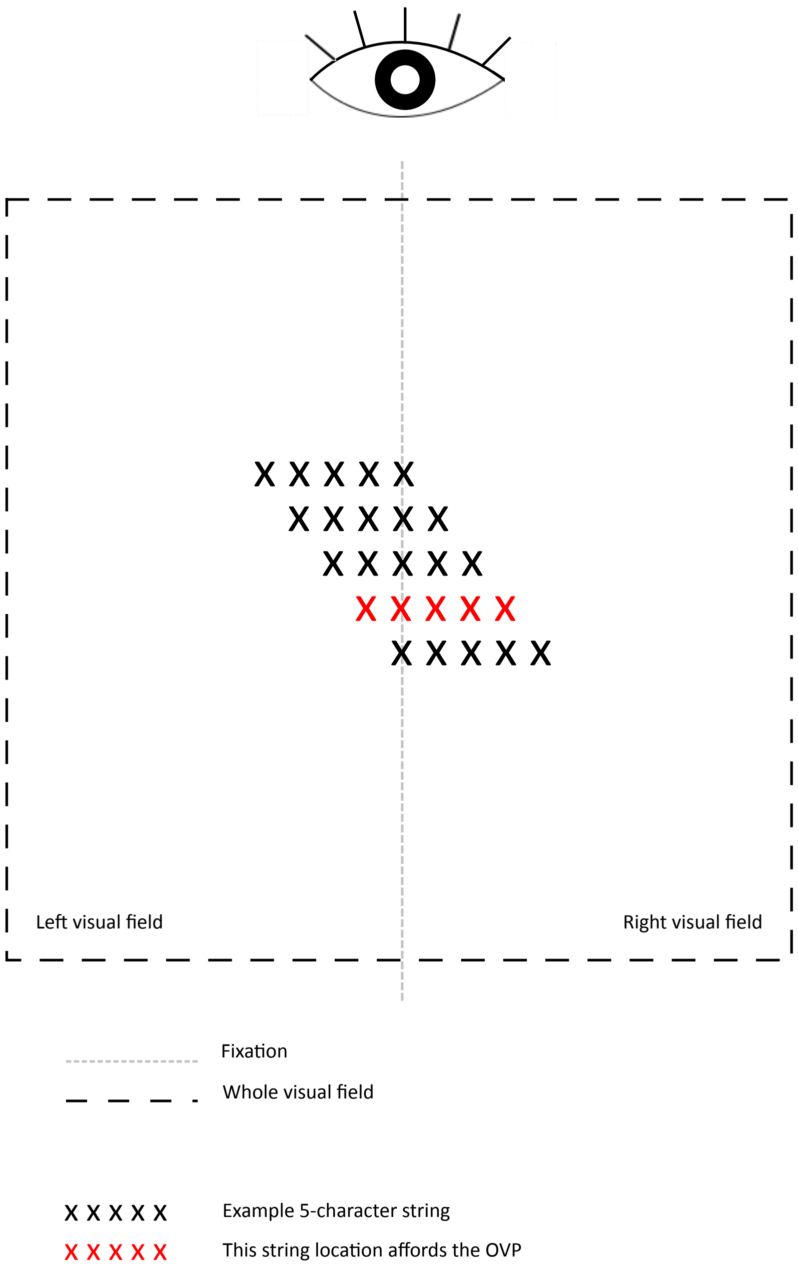

Figure 1.1: Illustration of stimulus locations used in my investigations of the viewing position (VP) curve.

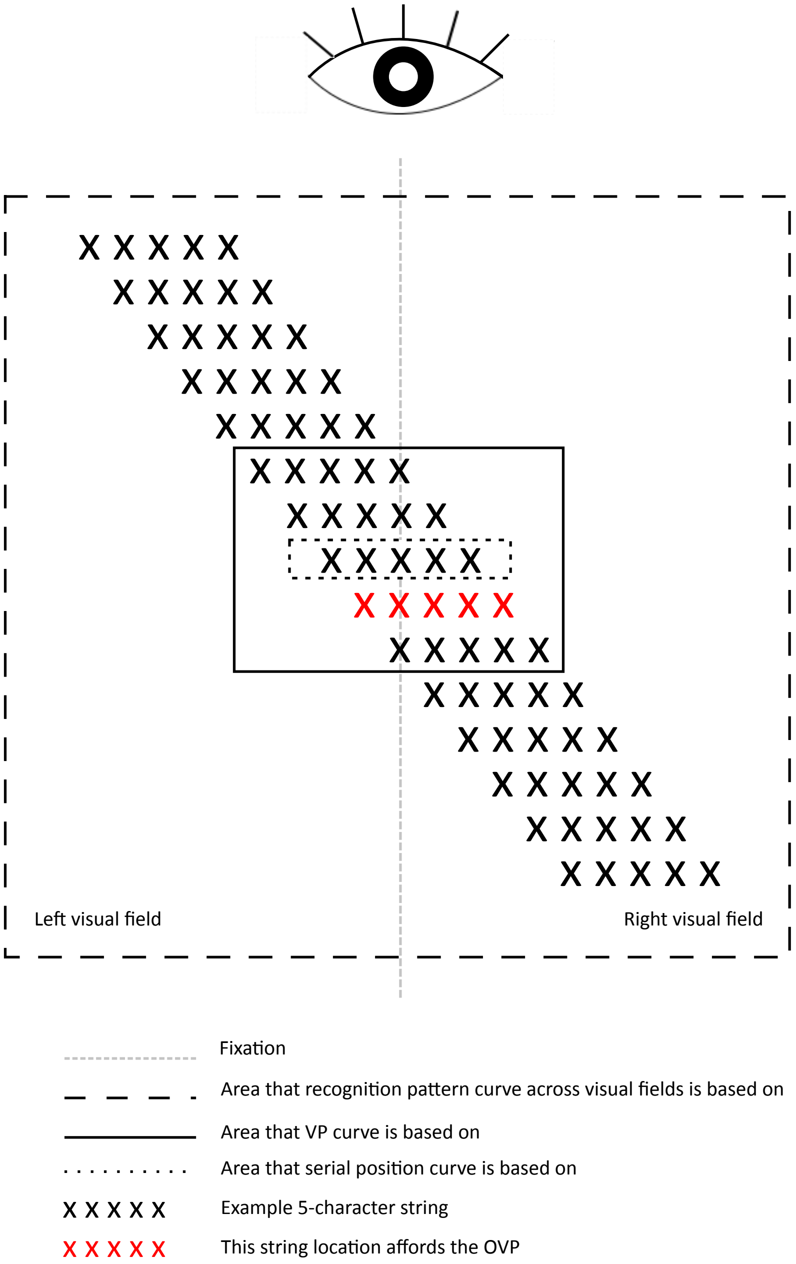

Figure 1.2: Illustration of stimulus locations used in my investigations of the VP curve.

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Chapter 2

Without a word: the beginning vs end asymmetry of viewing position effect is not specific to word processing

2.1 Abstract

Human performance in visual word recognition depends on where the eyes initially fixate within a word, the so called viewing position (VP) curve. The VP curve is characterized by an overall inverted U shape and by two asymmetric effects: (1) better recognition for fixations at the beginning than at the end of a word and (2) fixations at a left-to-center of a word being optimal, known as an asymmetric optimal viewing position (OVP) effect. Accounts for the asymmetric VP effects have been proposed; attention has centered on the left hemispheric specialization for words, perceptual learning during reading, and the informativeness (of the word identity) distribution within a word. However, it has been a hard time for research on visual word recognition disentangling the contributions among proposed mechanisms. For the VP curve of words, the behavioral changes due to the manipulations on either hemispheric language dominance, perceptual learning of language experience, or word

characteristics are inevitably interdependent to each other. To isolated contributions to the asymmetric VP effects due to perceptual learning, we exploited non-word letter strings to eliminate the contribution of word level processes. According to the cerebral laterality account, which reasons the asymmetric VP effects on the hemispheric differences for word processing, there should be no asymmetric VP effects for non-words. However, our results show the beginning vs end VP asymmetry as what the perceptual learning predicts. Moreover, further analysis on letter recognition in each visual field demonstrates better performance in the right visual field than in the left visual field. It is consistent with the perceptual learning for its proposed mechanism on the perceptual asymmetry between the visual fields. Our findings suggest the beginning vs end VP asymmetry is not specific to words. This study rules out the necessity of the hemispheric specialization for word processing to account for the beginning vs end VP asymmetry; the perceptual learning account alone can explain the beginning vs end VP asymmetry.

2.2 Introduction

Contemporary research on visual word recognition focuses on the front-end of visual word processing (Grainger, Dufau, Montant, Ziegler, & Fagot, 2012; Gomez, Ratcliff, & Perea, 2008; Carreiras & Grainger, 2004; Dehaene, Cohen, Sigman, & Vinckier, 2005). Indeed, a fundamental concern for visual word recognition models is how to represent lexical information such that letter identities and letter positions are encoded. Rather than presupposing a written word representation as a perceptual-free lexicon entry or a symbolic operator that does not require much consideration of visual constraints on processing of words, contemporary approaches include components of visual word processing to be compatible with the constraints of the visual system.

It has been well-documented that visual word recognition strongly depends on where the eyes initially fixate within a word. Given the drop-off in acuity from fixation (Anstis, 1974), visual recognition performance decreases symmetrically in the two visual fields as a nearly linear function of distance from fixation (Weymouth, Hines, Acres, Raaf, & Wheeler, 1928). The viewing position (VP) function of visual word recognition generally shares this inverse U-shaped pattern but is characterized by asymmetric drop-offs with lower performance while fixating at the word's end compared to at its beginning (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984).

A marked preference for word beginnings has methodological and theoretical consequences for the investigations on visual word recognition. VP function suggests that theories on lexical access with no parameters regarding to initial eye fixations may not be realistic if they seek to address human cognition on a basis of empirical behavioral performance. Moreover, with respect to VP curve's theoretical consequences, it may be helpful to make predictions for behavioral phenomena to test specific hypotheses of existing visual word recognition models. For example, O'Regan and Jacobs (1992) argued that their results of VP curve for low frequency words might speak against a left-to-right grapheme-to-phoneme translation strategy proposed by the dual-route models (Coltheart, 1978). This proposed strategy would expect to occur especially on difficult words, such as words with low frequency, which also expect to demonstrate a more dramatic shifted optimal viewing position (OVP) toward the word's beginning. Results from the naming task of O'Regan and Jacobs (1992) did not indicate such an effect, and instead it revealed a more centrally placed OVP for low frequency words on the lexical decision task. Methodologically, the reliable VP curve asymmetry raised a concern that words are conventionally present in a way that the eyes fixate at the middle of words for the majority of studies: at least some parts of effects then may be due to variations in VP curve rather than the key variables that are manipulated in the studies.

Exactly what contributes to VP function asymmetry, as well as the neural mechanisms to account for its relation to visual and/or word processing, however, are not well understood. It is unclear whether visuo-perceptual factors, or lexical factors, or both drive the asymmetric VP function. The asymmetric VP function leaves an open question of whether this asymmetry reflects the processes that decode words at the level of letters or in their entirety as whole words. One dominant hypothesis attributes the asymmetric VP function to LH dominance for language processing (Brysbaert, 1994; Brysbaert, Vitu, & Schroyens, 1996). This so-called cerebral laterality account is based on the proposal that a similar mechanism accounts for the VP curve asymmetry and the right visual field (RVF) advantage for word processing. Due to the anatomy of the human visual system, stimuli presented in the

RVF directly project to the left hemisphere (LH), which is the language dominant hemisphere for the majority of right and left handed people alike. On the other hand, stimuli presented in the left visual field (LVF) directly project to the right hemisphere (RH). According to cerebral laterality account, lexical information in the LVF/RH has to transfer to the LH before word processing can begin (Brysbaert et al., 1996; Stephan, Marshall, Penny, Friston, & Fink, 2007). Consequently, the processing of lexical information in the RVF, which initially projects to the LH is temporarily inhibited until the lexical information from RH/LVF arrives in the LH (Chiarello & Maxfield, 1996; Haegen & Brysbaert, 2011). This inter-hemisphere transfer from LVF/RH to the LH takes time, thereby producing an asymmetric VP curve that favors initial fixations at word beginnings.

To assess cerebral laterality account of the VP curve asymmetry, Brysbaert (1994) examined whether the VP curve asymmetry is larger for participants with typical left hemisphere language dominance than for participants with atypical right hemisphere dominance. Although group differences were small, the results were consistent with cerebral laterality account (Brysbaert, 1994). Moreover, Brysbaert et al. (1996) observed that the size of differences between the two groups increased with the number of letters that needed to be transferred from the LVF/RH to the LH (Stephan et al., 2007). However, even though group differences were reliably observed, individuals with right hemispheric language dominance did not show a word final superiority effect. The small shift toward a more symmetric VP function for individuals with right hemispheric language dominance suggests that at least part of the word-beginning benefits are likely due to other factors.

The differences in recognition accuracy across the two visual fields, as reflected in the asymmetric VP curve, do not merely reflect functional hemispheric asymmetries in word processing. Multiple studies have demonstrated greater letter recognition in the RVF than in the LVF as well as a steeper drop-off from fixation to the periphery in the LVF than RVF (Bouma, 1973; Nazir, O'Regan, & Jacobs, 1991). Based on these findings, Nazir proposed the multiplied letter identification probability (MLIP) model, which explains asymmetric VP curve in terms of differences in letter visibility in the two visual fields (Nazir et al., 1991; Nazir, Heller, & Sussmann, 1992). Without assuming any lexical influences, their estimates of VP curve are qualitatively similar to the empirical asymmetric VP function for words (Nazir et al., 1992). By using butterfly words (increasing font size for letters in the periphery), the further investigation showed that compensation for visual acuity could yield a symmetric VP pattern, but only for short words (Nazir, Jacobs, & O'Regan, 1998). The authors hypothesized that due to a lack of the retinal training in parafoveal vision (lack of perceptual learning), the magnification of letter size for long words is unable to compensate for letter visibility.

These observations on letter perceptibility regarding to their location on the retina (LVF/RVF; fovea/periphery) merged the explanations into the so-called perceptual learning account. Taken together with a preferred landing position (PLP), a similar-looking asymmetric viewing position that is computed from the distribution of landing sites in normal reading, the perceptual learning account proposed that asymmetric VP function is the result of a frequency-sensitive training mechanism with a PLP in normal reading. In other words, the differences in the letter perceptibility over various locations within a word are shaped by the way we learn to read. Asymmetric VP curve, thus, should be sensitive to low-level properties of reading habits like reading direction such that the asymmetric letter recognition effects would vary across languages that differ in reading direction. Consistent with this perceptual learning account, Nazir, Ben-Boutayab, Decoppet, Deutsch, and Frost (2004) showed that Hebrew readers recognize letters to the right of fixation better when fixating the center of a Hebrew letter string and the reverse for a Roman letter string. A confirmed role for perceptual learning in VP curve asymmetry, nevertheless, cannot rule out the possible contribution of functional hemispheric asymmetries. Comparing VP curve of French versus Arabic readers, Farid and Grainger (1996) observed a symmetric but not a reversed VP function for Arabic words, indicating neither a perceptual learning (due to reading direction) nor a cerebral laterality account solely can explain the asymmetry of VP curve.

The cerebral laterality and perceptual learning accounts concur that VP curve asymmetry reflects a processing benefit for words presented in the RVF. They differ, however, on the mechanism(s) responsible for the asymmetric VP function – namely, brain functional organization versus retinal perceptual learning. They also differ on whether they assume the critical unit of analysis for the processing asymmetry is the letter or the whole word. On the perceptual learning account, VP curve asymmetry for a word stems from the combined differences in letter visibility across the two visual fields, greater in the RVF. On the cerebral laterality account, VP curve asymmetry stems from processing differences at the word level: the word beginning benefit and RVF advantage both emanating from the language dominant LH processing of words.

Fixating a word's left-to-center position not only moves the fixation toward the beginning of a word but also leads to positioning the remainder of the word in the RVF. Fixating the beginning of a word thus is inevitably confounded with its positioning in the RVF, rendering it impossible to disentangle the cerebral laterality versus the perceptual learning account. With few exceptions, researchers have focused on letter recognition in words to investigate the VP effect. Yao-N'Dré, Castet, and Vitu (2013), for example, showed that VP curve asymmetry was significantly weaker in the lower visual field (in the periphery) than in the fovea, reinforcing a role for letter recognition in VP curve asymmetry. Kajii and Osaka (2000), on the other hand, reported a weaker VP curve asymmetry for vertical compared to horizontal displays of Japanese words (opposite to the perceptual learning prediction based on a stronger drop of visual acuity in the median), suggesting a role for language laterality instead. Although these studies reported modulations of VP curve asymmetry with changes in presentation formats, neither asymmetry due to word beginning benefit nor due to differences in perceptual visibility across the visual fields could be isolated from (either weaker or stronger) initial letter benefits on words.

One potential way to isolate the asymmetry due to word beginning benefit from that due to perceptual differences across the two visual fields might be to apply VP measurements to non-word letter strings, thereby eliminating the contribution of word level processes under the control of the left "language" hemisphere. By examining letter recognition as a function of fixation position and the letter-in-string position in non-word letter strings, any observed benefits due to fixating the beginning of string cannot be attributed to hemispheric differences for word processing as proposed by cerebral laterality account. Instead, whatever perceptual learning results from the attentional bias of reading direction (Nazir et al., 2004), retinal training from the preferred landing position (Nazir, 1993), or the stimulus-specific properties of linguistic materials (Nazir et al., 2004), VP curve asymmetry for a non-word letter string, if any, can be taken to reflect letter processing asymmetries without contributions from word-specific processes.

The bulk of the literature on the VP function for letter recognition is based letter strings presented wholly either in the left visual field or the right visual field. Various studies have tested letter recognition in random letter strings (Bouma, 1973), letters embedded in a series of Ks (Nazir et al., 1991), Xs (Nazir et al., 1992), or in digits (Kajii & Osaka, 2000). Fixation was either on the first or last letter in the string and the pre-designated target letters were not positioned at all possible locations within the string or relative to fixation positions. For example, studies of letter-in-string visibility (for example, Estes, Allmeyer, and Reder (1976)), the serial position effect (Tydgat & Grainger, 2009; Chanceaux & Grainger, 2012), and some VP effect literature on letter visibility (Nazir et al., 2004) used only central fixation. The common finding that letter visibility is greater in the RVF than LVF suggests that the perceptual asymmetry in two visual fields should be a critical factor in any investigation of VP curve asymmetry. However, there is a gap between perceptual asymmetry observed in one or the other visual field (in the periphery) and around center fixation (in the fovea). Whether there is a perceptual asymmetry (between slight left and right) around fixation, and if so, what the exact letter visibility function is and its relationship to the VP function for word recognition have not been systematically examined.

To date, only Stevens and Grainger (2003) provide a complete letter visibility function across all combinations of fixation and letter-in-string positions. Finding a symmetric VP function for letter strings, they concluded that variation in letter visibility could not explain the asymmetry observed with word stimuli. They hypothesized that the asymmetric letter visibility function widely reported in the literature might result from a bias due to stimulus presentation in one or the other visual field. The absence of an asymmetric VP function of letter visibility was then used to argue for the role of lexical informativeness within a word, specifically lexical constraints. This is a hypothesis proposed by Clark and O'Regan (1999), who demonstrated that an asymmetric lexical ambiguity pattern within a word could arise from calculations of lexical constraints. However, we obtained contradictory results from modeling based on Stevens and Grainger (2003) 's proposal. Smith, Chan, and Levy (2010) adopted an inverse-engineering approach to tease apart the contributions of perceptual learning and lexical information in words. Even when the lexical information within a word was taken into account, we found an asymmetric visual visibility curve contributing to VP curve asymmetry. We pointed out that Stevens and Grainger (2003) measured letter visibility in the character-within-mask recognition task, which is sufficiently unlike natural reading to explain why they might have observed a symmetric VP function. Some credence for this explanation comes from Nazir et al. (2004) who observed asymmetric letter visibility across the two visual fields, when pound signs and letters instead of just hash marks (in Stevens and Grainger (2003)) served as masks; presumably their masked encouraged readers to process the letter strings as if they were reading.

2.2.1 The present study

The present study investigates VP curve asymmetry in letter recognition. Our aim was to isolate the contributions to letter recognition due to perceptual learning from the contributions of processes due to LH language dominance as proposed by the cerebral laterality account. By using non-word letter strings, we explored the extent to which perceptual learning can account for VP curve asymmetry, and the extent to which VP curve asymmetry is tied to hemispheric specialization for language processing. We addressed this issue by examining (1) whether VP curve asymmetry could be obtained from non-word letter strings, (2) whether VP curve asymmetry could be dissociated from initial letter benefits, (3) whether the letter recognition is superior in the RVF than LVF. Designated target letters were embedded in non-word letter strings of ”k”s. Letter strings were presented randomly at positions spanning horizontally from one visual field to the other across midline with target letters occurring randomly at each position within the string. To encourage readers to treat the processing of the letter stimuli more like natural reading, hash marks as used in Stevens and Grainger (2003) were removed, and nonword letter strings were constituted from lower case letters (instead of upper case as in Stevens and Grainger (2003)) embedded in “k”s (as in Nazir et al. (1991)).

The absence of asymmetry on VP curve would point to a role for word specific processing on the VP effect. Asymmetry, on the other hand, would indicate that low-level learning could account for VP curve asymmetry. Moreover, the measure in letter recognition would allow us to examine a relationship between VP curve asymmetry and initial letter benefit. Taken advantages of the design, which target letters embedded at various locations within strings that presented across fixation, we would be able to compare target recognition probabilities on a basis of their relative location within a string. If VP curve asymmetry is merely an effect reiterating initial letter benefit on a dimension of where the target letter appears in a string, then data that shows VP curve asymmetry would show initial letter benefit as well, and vice versa for the absence of both of effects. On the notion of word specific processing, neither initial letter benefit nor VP curve asymmetry would appear with non-word letter strings that we used in the current study. There might be, however, VP curve asymmetry, suggesting a mechanism in which VP curve asymmetry involves may not be specifically for words. Alternatively, if the system is extremely sensitive to components of words, not only words but also letters, one would expect VP curve asymmetry no matter whether there would be initial letter benefit or not. Finally, if, in fact, non-word letter demonstrate the VP curve asymmetry, one can examine the notion of recognition asymmetry by comparing targets from each side of visual fields from strings at the same relative location across fixation. The visual asymmetry, if it is indeed observed, will fill a gap between perceptual asymmetry observed in one or the other visual field (in the periphery; Bouma (1973)) and around center fixation (in the fovea; the present study), charactering a more realistic parameters determining the VP curve asymmetry. The investigation on the contributions of letter recognition to the asymmetry of VP curve can thus offer multiple measures that address questions about the theoretical debates in the literature on the front-end of word processing.

2.3 Experiment 1: Letter Recognition in a Non-word Letter String

2.4 Method

2.4.1 Participants

Twenty-four students from the UCSD social sciences undergraduate subject pool participated in the experiment for either a course credit or monetary compensation. Participants had a mean age of 20.96 (range: 19-26). Six were male; eighteen were female. All of the participants were right-handed (as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Nine participants reported having a left-handed parent or sibling.

2.4.2 Stimuli and design

Strings of five lowercase letter k served as stimuli. The possible target letters were c, o, t, or f, and on any given trial one of these replaced one of the letter of the k-string. For half of the subjects, letter c and t served as target letters in separate sessions (one in each block), and o and f served as distractors in both sessions. For the other half, letters o and f were targets and c and t were distractors. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix. The strings were randomly divided into 25 conditions as a function of their presentation relative to fixation (fixation location) and as a function of target letter location within the string (target letter location). Each string was repeated 10 times in each block. Overall, 750 trials per block were distributed across 5 runs of 150 trials each (See Table 3.1, Appendix A).

2.4.3 Procedure

Participants performed a letter discrimination task (Figure 2.1B). A trial began with a fixation "+" flashed at the center of the computer screen for 500 msec. Once the fixation disappeared, a string of letters displayed for 20 msec. The string was followed by a blank screen until the participants made their responses. Participants were asked to indicate whether or not a target letter was embedded in the string by pressing "Yes" or "No" response keys as quick and as accurate as possible. For half of the participants, the "Yes" key were assigned to their right hand. For the other half, their left hand was assigned to the "No" key. After the response had been making, another blank screen followed for 480ms, after which the next trial appeared. Figure 2.1A displays a trial sequence. The experiment contained two blocks. In each block, participants pressed a button to discriminate the target character from among two possible distractors. Participants were given a short break after every run, around every seven minutes.

2.4.4 Data Analysis

Analyses of variance (ANOVAs). ANOVAs were conducted with five levels of fixation position (the center of a string was -2 to 2 letters away from fixation; the negative value represented that the string was presented to the left of fixation) and five levels of target letter position. Significant effects were followed by the Tukey's post-hoc analyses for the paired comparisons. Stevens and Grainger (2003) demonstrated a significant interaction as well as main effects of fixation position and letter location. We expected to obtain the same results. Indeed, the perceptual account would expect an interaction between target location and fixation position. Fixating at the beginning of string with a target at the 1st letter of a string would lead to better letter recognition, and vice versa for a fixation at the end with a target at the end of a string. Significant main effects of fixation position or target location were followed up with the linear trend analysis.

Linear trend analyses with fixation position and target location. To evaluate the VP pattern of non-word letter string, we conducted a linear trend analysis for fixation position. A significant linear trend with a processing benefit with a fixation at the beginning letter of a string, if so, would indicate the asymmetry of viewing position pattern for the non-word letter strings. Notably, by using the non-word letter string, we were able to distinguish the viewing position effect (fixation position) from the word initial benefits given that the target letter locations within a string were randomized, and the letter orders of a non-word letter string should not carry additional information (from a word level) to influence the performance. To confirm this attempt empirically, the separate linear trend analysis was conducted with letter position as well.

Point-to-Point Distance method for visual field asymmetry. To quantify the asymmetry between the two visual fields, we introduced a simple image matching method to compare the overall performance for targets presented in the left and right visual fields. A distance function was calculated with point-to-point distance (B. D. Ripley, 1976; B. Ripley, 1979; B. D. Ripley, 1981) to measure dissimilarities between the two visual fields. Point-to-point distance represents the real distance of behavioral performance (recognition accuracy or reaction times) observed in the left, $\vec{x}_L = (x_{L1}, x_{L2}, ..., x_{Lm})$ and right $\vec{x}_R = (x_{R1}, x_{R2}, ..., x_{Rm})$ visual fields. It is expressed as Equation 2.1

$$d_E = ||\vec{x}_R \ - \vec{x}_L||_2 = \sqrt{\sum_{i=1}^{m}(x_{Ri} - x_{Li})^2} \tag{2.1}$$

This distance denotes the dissimilarity between two points - in the present context, targets with same relative distance from fixation but one in the left the other in the right visual field. x is the observation for target recognition performance at a given string eccentricity and target eccentricity from fixation in either the left visual field (x_{Li}) or the right visual field (x_{Ri}). m stands for a total number of target presentation location in each visual field.

The positive versus negative value was then assigned according to the relative performance between the two visual fields, as Equation 2.2 and Equation 2.3

$$s = \sum_{i=1}^{m} x_{Ri} - x_{Li} \tag{2.2}$$

$$D_E = \begin{cases} d_E & if \quad s > 0 \\ -d_E & if \quad s \leq 0 \end{cases} \tag{2.3}$$

The distance function was computed for each subject and the t-tests were conducted against zero (the null hypothesis: there is no difference between the two visual fields). The dataset with two extreme fixation positions only and dataset containing all position fixation positions were both analyzed.

2.5 Results

Analyses of variance (ANOVAs). The effect of fixation position is highly significant (Accuracy: F (4, 92) = 22.1.29, $p < 0.0001$; RTs: F (4, 92) = 19.73, $p < 0.0001$). Tukey post-hoc analysis shows that recognition accuracy and Reaction Times (RTs) is significantly lower when fixation position was at the string's end than at any other viewing position, indicating that the function relating to fixation position to recognition is asymmetric (See Figure 2.2). The main effect of target letter position is also significant (Accuracy: F (4, 92) = 4.33, $p < 0.005$; RTs: F (4, 92) = 4.27, $p < 0.005$). Tukey post-hoc analysis on target location, however, does not show significant accuracy differences between any two of target positions (See Figure 2.3). There is a significant interaction between fixation position and target letter position (Accuracy: F (16, 368) = 8.23, $p < 0.0001$; RTs: F (16, 368) = 3.34, $p < 0.0001$). Multiple comparison tests show that accuracy of fixation at the end of the string is significantly lower than other fixation positions when the target letter position is in the first half of the string (1-3 out of 5). This result can be better visualized with Figure 2.4, which plots recognition probability as a function of fixation position with each curve based on the target at a certain position. For the targets positioned in the first half of the string, they revels typical asymmetric VP patterns with better performance while fixating at the beginning letter of a string. By contrast, for the targets positioned at the 4th or 5th letter locations, the pattern is relatively symmetric and is dominated by visual acuity that a small processing benefit while fixating at the center of a string. Figure 2.5 plots recognition probability as a function of the target position relative to fixation. Recognition accuracy is mostly dominated by target distance from fixation, more so for targets in the LVF than in the RVF, while the drop-offs from fixation is smaller for targets at the first or last letter position within a string.

Linear and quadratic trend analyses with fixation position and target location. Recognition averaged over all possible target letter position varies as a function of initial fixation position with a significant linear trend (Accuracy: t (95) = 3.80, $p < 0.0001$; RTs: t (95) = -2.83, $p < 0.01$), and quadratic trend (Accuracy: t (95) = -7.37, $p < 0.0001$; RTs: t (95) = 8.40, $p < 0.0001$) (See Figure 2.2). Target position, however, shows no significant linear trend (Accuracy: $p > 0.85$; RTs: $p > 0.50$), but does show a significant quadratic trend for accuracy only (Accuracy: t (95) = -7.37, $p < 0.0001$; RTs: $p > 0.10$) (See Figure 2.3).

Similarity measure between the two visual fields: point-to-point distance. ***Fixations on the first or last character of string only.*** The subset of data included in this analysis displays in Figure 2.6. The similarity measure demonstrates a reliable visual field asymmetry. For both recognition accuracy and reaction times, there is a significant dissimilarity between targets presented in the left and right visual fields was evident for letter string (Accuracy: t (23) = 3.52, $p < 0.001$; RTs: t (23) = 3.25, $p < 0.005$).

Similarity measure between the two visual fields: point-to-point distance. ***All possible fixation positions across visual fields.*** Overall pattern of letter recognition for the entire dataset included in this analysis is displayed in Figure 2.6. It shows visual field asymmetry - a significant dissimilarity between the two visual fields for recognition accuracy and reaction times (Accuracy: t (23) = 2.71, $p < 0.01$; RTs: t (23) = 2.66, $p < 0.01$).

Summary of Main Results

Non-word letter strings demonstrate an asymmetric VP pattern in which average letter recognition (accuracy and RTs) over letter location is higher while fixating at the beginning of a string than at the end. By contrast, average letter recognition over target letter position does not demonstrate asymmetric pattern for a target letter at either at the beginning or the end of a string. Similarity measure between recognition patterns in two visual fields reveals RVF superiority in letter recognition.

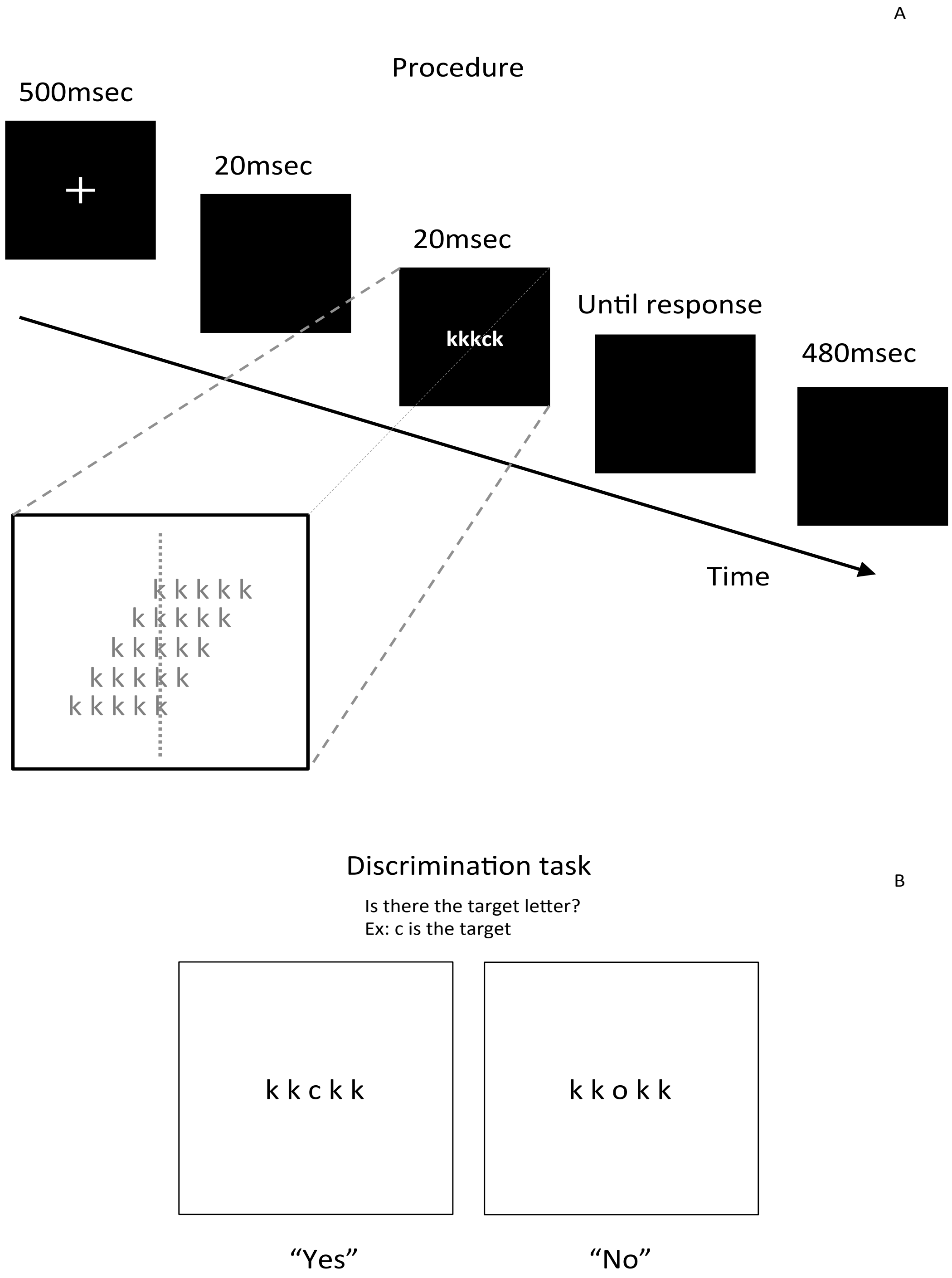

Figure 2.1: Procedure and task. A: procedure for a single trial in viewing position paradigm. B: Example of letter discrimination task used in Experiment 1.

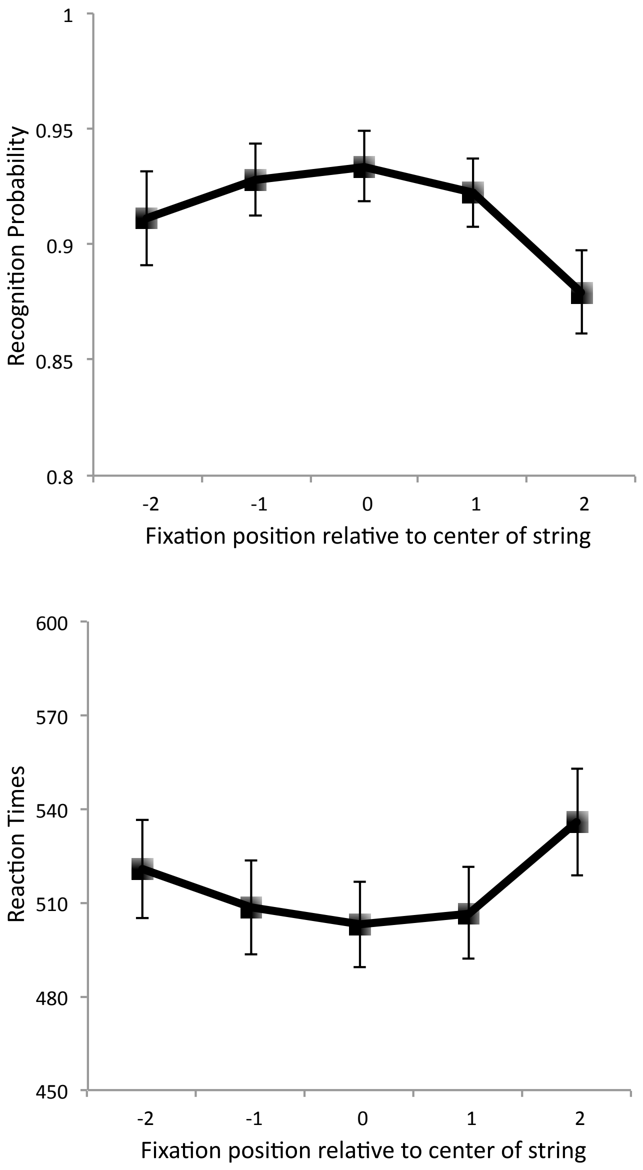

Figure 2.2: Two VP curves for recognition accuracy and speed for non-word letter strings. Note the asymmetric beginning vs end viewing position effect for non-word letter strings: letter recognition is more accurate and faster when eyes initially fixate the beginning of a non-word letter string. Top panel, character recognition as a function of fixation position collapsed over target positions. Bottom panel, recognition times for correct character recognition as a function of fixation position collapsed across target positions.

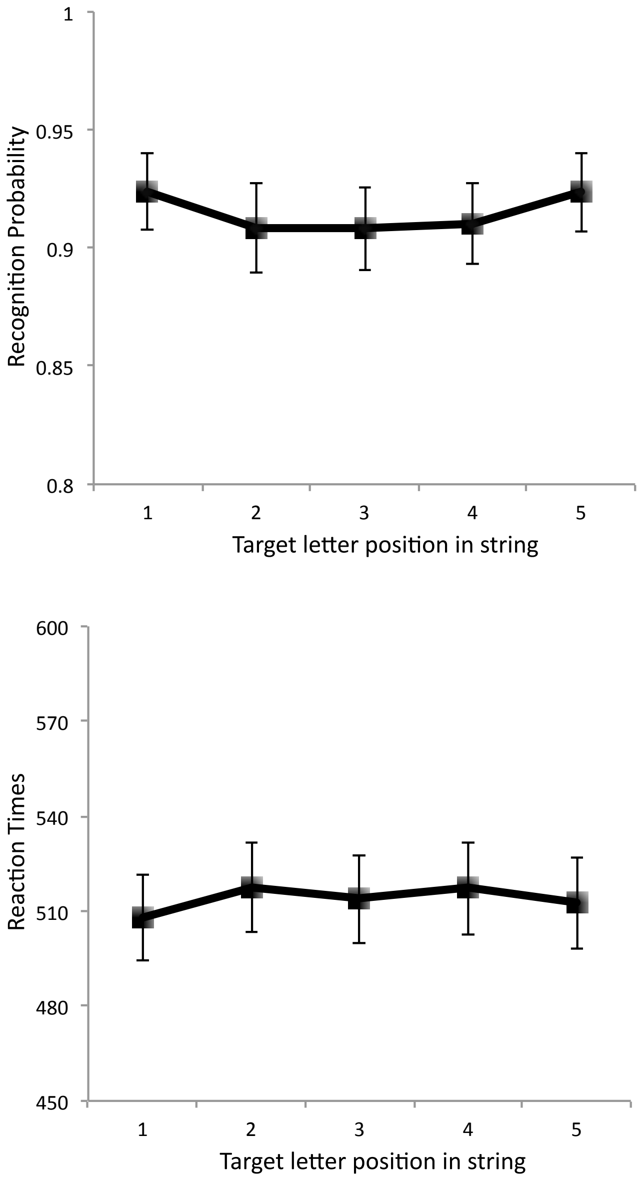

Figure 2.3: Target letter position function for non-word letter strings. Quadratic but not linear trends suggest recognition benefits for the two extreme target letter locations; no initial letter benefit is found. Top panel, character recognition probability as a function of target letter position, collapsed across fixation positions. Bottom panel, reaction times for correct character recognition as a function of target letter position, collapsed across fixation positions.

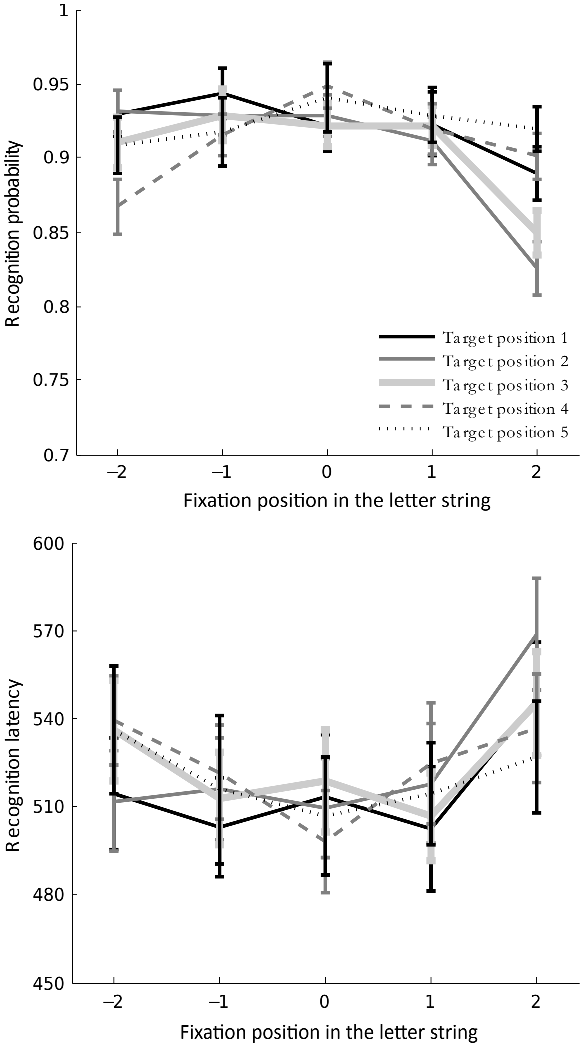

Figure 2.4: Superimposed recognition curves for each target letter position in non-word letter strings. VP curve asymmetries are more pronounced for target letter positions in the first than second half of a string. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

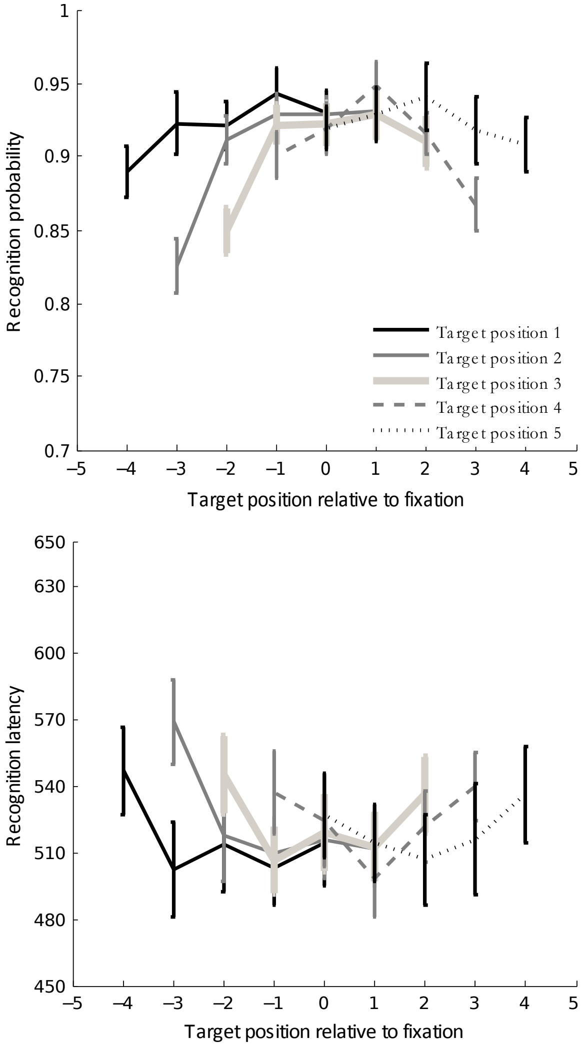

Figure 2.5: Superimposed recognition curves as a function of target letter distance from fixation for non-word letter strings. Recognition performance declines as a function of target letter distance from fixation, more so in the LVF than RVF. This visual difference contributes to the asymmetric viewing position curves seen for targets in the first vs second half of a string. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

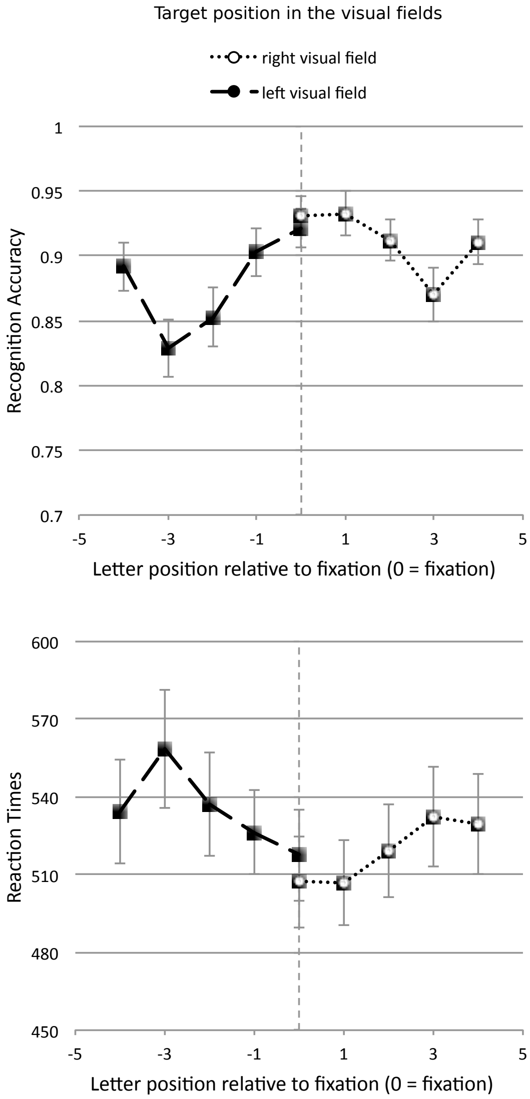

Figure 2.6: Recognition as a function of target distance from fixation for non-word letter strings. Recognition of targets in letter strings presented in the either LVF or RVF. Recognition performance declines as a target moves away from fixation, more so in the LVF than RVF. Top panel, accuracy of character recognition as a function of target distance from fixation. Bottom panel, reaction times of correct character recognition as a function of target distance from fixation.

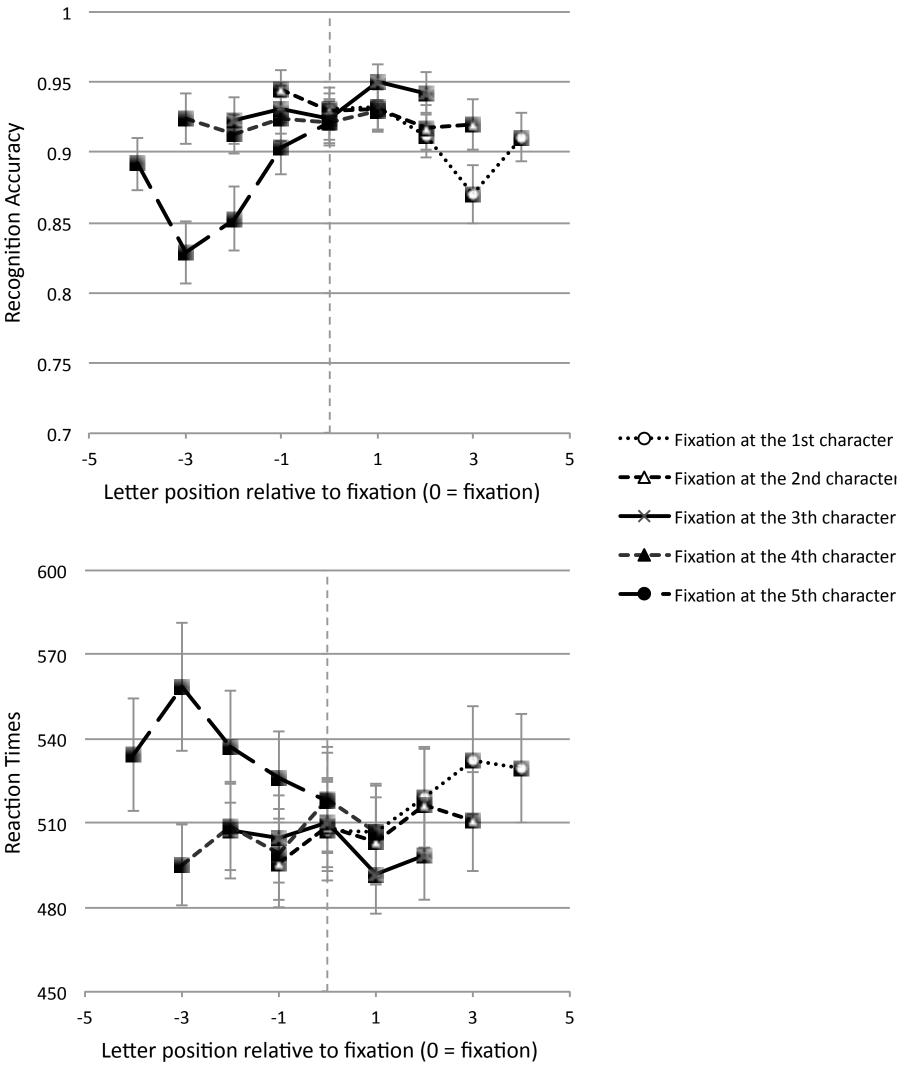

Figure 2.7: Function of target distance from fixation for non-word letter strings: fixations at all possible letter positions in a string. Data points include all fixation positions - fixation on the first character (the rest of characters being in the right visual field - RVF), fixation on the 2nd character, fixation on the 3rd character, fixation on the 4th character, fixation on the last character (the rest of characters are in the left visual field - LVF). Top panel, character recognition accuracy as a function of target distance from fixation. Bottom panel, reaction times for correct character recognition as a function of target distance from fixation.

2.6 Discussion

At a general level, this experiment sought to determine the extent to which visual asymmetry on letter recognition due to perceptual learning contributes to VP curve asymmetry. We addressed this issue by examining (1) whether VP curve asymmetry could be obtained with non-word letter strings, (2) whether VP curve asymmetry could be dissociated from initial letter benefits, (3) whether the letter recognition is superior in the RVF than LVF while letters are embedded in a non-word letter string (compared to those which were in a word) that are presented spanning around fixation (compared to those which is in one or the other visual field). We also examined whether or not the impacts of either these aspects would be modulated by the interplay between fixation and target's location in a string.

Our results show that VP curve is asymmetric for non-word letter strings. This VP pattern shows a linear trend of fixation in which average recognition accuracy is better when initial fixation is at the first letter of string than at the end. The argument that VP curve asymmetry reflects word specific processing, thus, cannot explain the observed VP curve asymmetry in the current study with the non-word letter string. Moreover, recognition accuracy over target positions in a string does not show a linear trend - there is no processing benefit for a target letter at first letter position compared to those which is positioned at the end of a string. By contrast, initial letter benefit is commonly found in real words: initial letters in a word are better recognized than letters at the end of a word. If the processing asymmetry obtained with the VP pattern merely reflects initial letter benefit, then the absence of initial letter benefit from non-word letter string would expect the absence of viewing position asymmetry. However, this was not what we observed, suggesting that the viewing position effect could be dissociable from initial letter benefit. Whatever factors contribute to VP curve asymmetry with non-word letter strings, therefore, can be isolated from contributions due to initial letter benefits (in a word or in a letter-string) and LH specialization on word processing.

While contributions due to perceptual learning are the most likely candidates, we examined specific hypothesis of perceptual learning that VP curve asymmetry could be attribute to RVF superiority in letter recognition. Our analysis for the similarity measure showed that the patterns of letter recognition between the two visual fields, given the performance on same the target distance to fixation of strings that mirror to each other at their locations, are significantly dissimilar to each other. Specifically, letter recognition is better when a target letter positions in the RVF than in the LVF. This is the case in general regardless whether or not a string is presented unilaterally in one side of visual field or it is spanning across fixation. This pattern of results is in accord with reports of better letter visibility in the RVF with the presentations of an isolated letter or a letter embedded in the string while presenting the entire string in either one of visual fields (Bouma, 1973; Nazir et al., 1991, 1992; Kajii & Osaka, 2000). By contrast, Stevens and Grainger (2003) found no asymmetry between the two visual fields. They argued that a superior visibility for letters presented in the RVF was due to a specific bias, probably an attention bias, which was induced by presenting the entire string in one or the other visual field. If the asymmetry is due to this attention bias, then the VP pattern should not be asymmetric unless the same experimental parameter, the biased presentation at a certain location in the visual fields, induces the attention bias on letter recognition. However, we found the asymmetry of VP pattern while presented locations were randomized and spanning across fixation. Specifically, the attention bias that could be induced by the way of experimental presentation could not explain the superior letter recognition in the RVF found in the current study. Notably, the argument here that the attention bias does not induce the RVF superiority does not exclude the possibility that some attention factors may modulate the processing differences between the two visual fields. For example, an attention bias due to the learned reading direction may modulate letter recognition depending on the visual field that the target presents. It is exactly a core idea that the perceptual learning account centers on: reading preference shapes processing on a familiar visual item (such as a word) at specific location. Previous studies have shown that the RVF superiority found in the languages that are read from left to right does not exist any more while tested in the languages that are read from right to left (Nazir et al., 2004).

A closely review on recognition pattern may reveal a hint of why there was a null result for recognition asymmetry between the two visual fields in Stevens and Grainger (2003). Figure 3 in their paper (as the one in Figure 2.5 in the current study) plotted the factor that combined target letter position and its distance from fixation. It showed that recognition probability decreased from fixation, more so for targets in the LVF than RVF, except for the targets at the first versus last letter location of a string. Targets at first letter location of a string (across all presented target distance from fixation) are especially better recognized than other target locations. Since the viewing position paradigm operated by shifting a string location to manipulate fixation position within a string, targets at the first letter location are always located somewhere in the left side of fixation if it is not directly fixated. Therefore, the averaged recognition probability in the LVF was likely boosted to the level of the averaged recognition probability in the RVF. By contrast, as visualized in Figure 2.5, the current results showed a similar overall trend of recognition drop-offs with distance and there was no special processing benefit for the targets that position at the first letter of a string.

Searching in the literature, the Modified Receptive Field (MRF) hypothesis might provide a possible foundation for the special processing benefit for the first letter in a string found in Stevens and Grainger (2003). The central idea of MRF hypothesis is that a special perceptual adaptation for letters results in a larger crowding in the LVF (Grainger, Tydgat, & Isselé, 2010; Tydgat & Grainger, 2009; Chanceaux, Mathôt, & Grainger, 2013; Chanceaux et al., 2013). According to the MRF hypothesis, first letter in a string (that usually presents in the LVF) is better recognized because of a relative larger release of crowding in the LVF [1]. However, the same reasoning is hard to explain the VP curve of real words: if this huge release of crowding for the first letter should result in no visual asymmetry between the two visual fields as seen in Stevens and Grainger (2003), then the same null asymmetry should also happen for words, which we know is not the case. A null effect of visual asymmetry and an exceptional initial letter benefit in Stevens and Grainger (2003) could not fit easily to the understanding of theory (hypothesis) in the literature and/or data driven findings. The current findings, by contrast, reconciled the findings in the literature on visual perception and letter recognition.

Furthermore, since the similarity measure in the current study was based on

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[1] The asymmetry in crowding between visual fields proposed by the MRF hypothesis could be an alternative explanation to account for RVF superiority in letter recognition. It could be potentially critical to the proposed mechanisms of perceptual learning account that it attributes RVF superiority in letter recognition solely to a steeper visual acuity drop-off in the LVF. However, the discussion on visual crowding, visual acuity, and how one or both of them influence the recognition performance is beyond a scope of current issue (on whether or not VP curve asymmetry solely relies on LH specialization on word processing). Details will be discussed in Chapter 4.

distance function (the value that quantifies the dissimilarity between visual fields) that was computed with a pair of letter recognition from the targets at the same relative distance in the strings that mirror each other in two visual fields, this measure allows two additional inferences to be drawn. First, letter recognition is superior in the RVF given that target distance from fixation has been considered. Although this does not directly prove the notion that the superiority is due to a steeper visual acuity drop-off in the RVF than LVF as proposed by the MLIP model (Nazir et al., 1992), this is consistent with their findings based on an experiment that was designed specifically for examining the target distance functions in each visual field. Second, the fact that a pair of target letters are from the strings that mirror each other remains the equal number of letters that present in the targets' visual field. The impact of the number of letters surrounding the target letter, referred as crowding in Chanceaux et al. (2013), has been shown to be larger in the LVF than RVF specifically for letters (but not for other visual objects). In our case, the similarity measure show that letter recognition is superior in the RVF given that the number of surrounding letters in the same visual field as the target has been considered as well.

Our findings thus suggest that viewing position asymmetry is not solely due to LH lateralization for word processing. Recognition asymmetry that shows a benefit to fixate initially at the beginning of a word can generalize to non-word letter strings. This observed recognition asymmetry on fixation position within a string is reconciled with visual field asymmetry that letter visibility is better in the RVF than in the LVF. One might argue against that the observed VP curve asymmetry for non-word strings is due to visual field asymmetry resulted from perceptual learning, opting instead that the observed asymmetry reflected LH lateralization in language processing in a broad sense because letters are a typical component of words. On this view, the contribution of cerebral laterality is generalized beyond word specific processing: left-hemisphere lateralization for the multi-level language processing including letter recognition. While this is a possible reinterpretation, it articulates grey definitions between original cerebral laterality account and the perceptual learning account. First, the view that better recognition in the RVF might attribute to LH lateralization for letter string has been regarded as evidence for perceptual expertise on language materials such as words and letter strings (McCandliss, Cohen, & Dehaene, 2003). Second, the cerebral laterality account (Brysbaert, 1994; Brysbaert et al., 1996) is not built upon a general notion of (multi-level) language processing. Instead, it resides on a strong position of early integration hypothesis on word processing. That is, all letter information transfer and combine in left hemisphere before word processing can begin (Brysbaert et al., 1996; Stephan et al., 2007). The processing asymmetry among fixations, according to cerebral laterality account, is a product of a need to transfer information letter-by-letter to left hemisphere before word processing begins - the more letters to transfer, the longer the time before word processing begins (Brysbaert, 1994; Haegen & Brysbaert, 2011; Haegen, Brysbaert, & Davis, 2009; McCormick, Davis, & Brysbaert, 2010; Whitney, 2001).

A further examination on the perceptual learning account, therefore, should question on exactly what extent to which recognition asymmetry would be generalized to other types of visual object. According to the perceptual learning account, visual asymmetry reflects perceptual adaptation due to perceptual learning while acquiring reading skills. The perceptual learning account argued that this visual adaption on visual field asymmetry could not be generalized to every visual domain, and it would be instead limited to familiar reading components such as words and letters. An open question that cannot answer based on the current findings with non-word letter strings though is whether or not recognition asymmetry depends on the stimulus-specific adaptation for letters. On the one hand, non-word letter strings should be the minimally plausible visual configurations (relevant to words) that demonstrate recognition asymmetry across visual fields, if perceptual learning of reading shapes visual processing in a specific domain relevant to visual word recognition. On the other hand, if perceptual learning shapes visual processing in general, then recognition asymmetry is expected regardless of types of stimuli, letters or any visual objects. Yet, we know of no studies that directly compare results from letter recognition tasks that provide measures of visual asymmetry in the viewing position paradigm for those with character recognition using other visual characters such as symbols, which are not necessary visual components of language. In Chapter 3 and Chapter 4, by using the same design - a target discrimination task in the viewing position paradigm, we would test the extent to which perceptual learning shapes visual asymmetry for non-letter symbol strings and other visual objects that are not distinguished by letter-features.

2.7 Summary and Conclusions

Our results with non-word letter strings extend previous studies on VP curve asymmetry in several important ways. First, they demonstrate that VP curve asymmetry is not limited to processing on words; instead, letter recognition asymmetry can be generalized to non-word letter strings. Second, our analysis illustrates that VP curve asymmetry with fixation position within a string can be dissociated from initial letter benefit - neither evidence for better recognition for a letter positioning in the beginning of a string nor evidence that it contributes to VP curve asymmetry. These two findings are particularly relevant to a debate on the proposed mechanisms of VP curve asymmetry. The cerebral laterality account that emphasizes on the hemispheric differences, especially word processing, is not sufficient to account for the current findings. The measurement of letter recognition asymmetry provided by current experimental setups, therefore, fills a methodological gap between presenting strings in one or the other visual field (in the periphery) and around fixation (in the fovea). Finally, our finding on visual field asymmetry suggests that the VP curve asymmetry may be a consequence of a RVF superiority of letter recognition. Perceptual components that impact on letter recognition between the two visual fields, as shown in the current case, clearly determines the direction of asymmetry for the VP patterns - fixating at the beginning of a string that benefits from RVF superiority on letter recognition can lead to the beginning vs end VP asymmetry. A future work would examine the extent to which perceptual learning of reading shapes visual processing. In conclusion, the present study using non-word letter strings demonstrates the beginning vs end VP asymmetry, which is commonly found with word stimuli, indicating recognition asymmetry without a contribution of word specific processing.

This implicates more than a view on LH lateralization on word specific processing while investigating on visual word recognition.

2.8 Acknowledgement

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2.9 Appendix A

Table 2.1: The number of trials and target letters for each block used in Experiment 1

First half of subjects						
			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	c	25	10	250	750
	Distractors	o	25	10	250	
		f	25	10	250	
Block 2	Target letter	t	25	10	250	750
	Distractors	o	25	10	250	
		f	25	10	250	
Second half of subjects						
			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	o	25	10	250	750
	Distractors	c	25	10	250	
		t	25	10	250	
Block 2	Target letter	f	25	10	250	750
	Distractors	c	25	10	250	
		t	25	10	250	

No. of conditions - 5 locations of letter string x 5 positions of target letter within a string

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Chapter 3

Stimulus-specificity on the asymmetry of viewing position effect

3.1 Abstract

In Experiment 1 of this dissertation, we demonstrated the beginning vs end viewing position (VP) asymmetry with non-word letter strings. Since the contribution to the beginning vs end VP asymmetry due to left hemisphere specialization for word processing was eliminated with non-word letter strings, the findings were taken as evidence that the observed beginning vs end VP asymmetry might be attributed to the right visual field (RVF) superiority for letter recognition. Specifically, according to the perceptual learning account, this visual asymmetry in letter recognition is due to a perceptual tuning that is specific to visual word recognition: stimulus- and location-specific perceptual adaptation for letters and words. One empirical question is whether the perceptual adaptation due to perceptual learning while acquiring reading skills is stimulus-specific (i.e., limited to words and letters) or could be generalized (i.e., to any type of visual objects). To determine the extent to which recognition asymmetry reflects perceptual adaptations due to perceptual learning of reading, the

current study investigate whether the VP curve asymmetry reflects domain-specific perceptual adaptation that is specific to linguistic stimuli or applies to visual processing more generally. We show the beginning vs end VP asymmetry for non-linguistic symbol strings and symmetric VP curves for ring sequences, which consisted of characters that are not distinguished by letter-like features. These results indicate that RVF superiority for character recognition due to perceptual learning of reading is neither general to any visual objects nor limited to words (i.e., letters). Instead, this perceptual learning effect seems to be domain-specific to linguistic relevant visual configurations (ex: symbols with letter-like features). By discussing the stimulus-specific and location-specific effect of perceptual learning, some empirical and theoretical, we explain how perceptual learning during reading contributes to the asymmetric VP curve on a basis of perceptual tuning due to reading that leads to perceptual asymmetry between the two visual fields.

3.2 Introduction

Extensive training in visual perceptual tasks leads to improved performance (Ramachandran & Braddick, 1973; Fahle, Edelman, & Poggio, 1995; Fiorentini & Berardi, 1980). Perceptual learning typically demonstrates stimulus-secificity and location-specificity: the improvement is limited to the stimuli that are similar to the trained stimulus at the trained location in visual space (Li, Piëch, & Gilbert, 2004; Sigman et al., 2005; Fahle & Morgan, 1996; Westheimer, 1996; Ball & Sekuler, 1987; Karni & Sagi, 1991). This specificity for stimulus type and location suggests that at least some components of perceptual learning take place in early visual areas (Karni & Sagi, 1991; Ball & Sekuler, 1982; Poggio, Fahle, & Edelman, 1992; Berardi & Fiorentini, 1987; Maffei & Fiorentini, 1976; McKEE & Westhe, 1978). This view is by single unit recordings and fMRI studies, in which visual perceptual learning elicits reliable changes in the functional properties of neurons in the primary visual cortex (Crist, Li, & Gilbert, 2001; Schwartz, Maquet, & Frith, 2002; Schoups, Vogels, Qian, & Orban, 2001; Furmanski, Schluppeck, & Engel, 2004). Given this impact of learning in visual perception, Nazir and colleagues proposed that learning to read, as viewed an extensive perceptual training, may lead to location-specific tuning for letters due to perceptual tuning in the early visual area for the particular visual configurations that are used in reading (Nazir, 2000; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004). This proposal is based on the similarity between behaviors in eye movements and in viewing position (VP) patterns for successful word recognition. In normal reading, a distribution of eye landing is characterized by a preferred landing position (PLP), the most frequent landing site located somewhere near the beginning of a word. Similarly, viewing position patterns within a word demonstrate a preferred location toward the beginning of a word: word recognition is better when the eyes initially fixate the beginning than the end of a word. Given this perceptual learning account, the perceptual asymmetry in letter recognition between the two visual fields contributes to the asymmetric VP curve in visual word recognition (Nazir et al., 2004).

Following Nazir and colleagues, in Experiment 1 of this dissertation we showed evidence of RVF superiority for letter recognition, which could lead to the beginning vs end VP asymmetry even when letters are embedded in non-word letter strings. This could be by perceptual adaptation for letters due to perceptual learning during reading. This is potentially critical to the understanding of how the changes in early visual processing may impact visual word recognition. Indeed, recent studies on literate adults reveal that the enhanced neural activations due to literacy is not limited to areas known for language processing such as left fusiform gyrus but also extends to the early visual areas in V1/V2 and V3/V4 (Dehaene et al., 2010; Szwed, Qiao, Jobert, Dehaene, & Cohen, 2014).

An open question with regard to the stimulus-specificity of perceptual learning during reading is whether or not this perceptual tuning is specific to letters. According to what is known about perceptual learning, location-preferential perceptual tuning should be limited to stimuli configured with linguistic relevant visual components, for example, whether or not it extends to non-letter symbols. Some brain-imaging studies have found that symbol characters that share some degrees of visual similarity to letters show enhanced activations in early visual cortex compared to other visual objects. For example, larger activations are seen in response to line-drawn horizontal strings than to controlled scrambles in early visual cortex (Szwed et al., 2011). Perceptual training with symbol characters could induce such enhanced activations in primary visual area to them (Dehaene, Cohen, Sigman, & Vinckier, 2005). Furthermore, statistical computational approaches point to a similarity in the structures of letters and symbols to the analysis of visual configurations of written system. Changizi, Zhang, Ye, and Shimojo (2006) showed that all writing systems make use of similar visual configurations. Given a reproducible statistical distribution over the visual configurations of written systems to natural scenes, they further suggested that written symbol structure through human history may have been selected to match those found useful for nature scenes. Their view reconciles with the position that perceptual learning during reading should not only be for letters but also for symbols consisting of visual configurations shared by human writing systems. Human brains may well treat letters and symbols similarly given the structures that they share, and if so, whatever this special process may be, it should be differentiated from processes to other visual objects.

Also an issue is the generalizing of the location specificity of visual perceptual learning (Ball & Sekuler, 1982; Poggio et al., 1992; Nazir, 2000; Nazir et al., 2004; Dehaene et al., 2010). For example, perceptual learning of difficult conjunction detections is location-specific while perceptual learning of simple feature detection is not (Szwed et al., 2014). While perceptual learning of complex pattern recognition is consistently found to be location specific (Szwed et al., 2011; Dehaene et al., 2005), the literature on simple orientation discrimination reports mixed results for effects that are location specific and effects that generalize to untrained location in visual space (Changizi et al., 2006; Bao, Yang, Rios, He, & Engel, 2010). Likewise, let's consider the VP curve asymmetry. According to a perceptual learning account (Nazir, 2000; Nazir et al., 2004), the VP curve asymmetry is due to a combination of stimulus specificity and location specificity. With regard to perceptual learning during reading, words and letters, which may be the main visual stimuli that human brains are perceptually trained to recognize, are somewhat analogous to complex pattern stimuli in a difficult perceptual learning task. The improvement in recognition due to preferred landing location in normal reading, as reflected in the asymmetric VP curve, demonstrates an effect of location specificity. Taken together, we hypothesize that the VP curve asymmetry will not generalize to other visual objects, especially stimuli that are visually simple in the configuration. First, if it is agreed that words and letters, which receive perceptual training during reading, are analogous to complex pattern recognition in a difficult perceptual learning task, then the improvement due to perceptual learning in reading should be stimulus specific and should not generalize to simple pattern recognition. Second, if simple visual features and not letters per se (relative complex visual configurations), are indeed the visual stimuli that our brains are perceptually trained to recognize via perceptual learning during reading, then the perceptual adaptations that these simple stimuli engage should not reliably demonstrate location specificity, and thus should not yield the beginning vs end VP asymmetry.

3.2.1 The present study

The present study investigated the asymmetry of VP curve using non-letter symbol strings (Experiment 2) and non-linguistic ring sequences (Experiment 3). Our aim was to examine the extent to which perceptual learning during reading shapes recognition asymmetry as revealed in the VP curve asymmetry. To determine the extent to which the VP curve asymmetry is tied to specific perceptual tuning for letter recognition, Experiment 2 investigated whether non-letter symbol strings would also yield the beginning vs end VP asymmetry. The absence of asymmetry on the VP curve would support the hypothesis that the VP curve asymmetry is due to perceptual adaptation specifically for letters. On the other hand, if the asymmetry is indeed observed, it would suggest that perceptual learning during reading is not limited to letters and can extend to symbols that share common features of letters. We hypothesized that non-letter symbol strings would show the beginning vs end VP asymmetry, reflecting better symbol recognition in the RVF due to perceptual tuning for the particular visual configurations used in reading. To determine whether this perceptual adaptation due to perceptual learning of reading can be generalized to other visual objects, Experiment 3 investigated whether there would be the beginning vs end VP asymmetry for character recognition more generally by using ring sequences which were not distinguished by letter-like features. Based on stimulus- and location-specificity of perceptual learning (Ahissar & Hochstein, 1997), we hypothesized that there would be no beginning vs end VP asymmetry, a symmetric VP curve for non-linguistic ring sequences. In sum, we expected the beginning vs end VP asymmetry only for stimuli that consist of linguistic relevant visual configurations: no beginning vs end VP asymmetry for non-linguistic ring sequences. Comparing of VP curves across types of visual stimuli would provide critical evidence about the extent to which the VP curve asymmetry could be explained by the perceptual learning account, via perceptual adaptation in the early visual area on visual word recognition.

3.3 Experiment 2: Symbol Recognition in a Non-letter Symbol String

Experiment 2 was designed to determine whether the human visual system also treats non-letter symbol strings similar to non-word letter strings. If a string of non-letter symbols also yields the beginning vs end VP asymmetry similar to what have seen for strings of letters, then we can conclude that the beginning vs end VP asymmetry is not specific to letters.

3.4 Method

3.4.1 Participants

Twenty-four students from the UCSD social sciences undergraduate subject pool participated in the experiment for either course credit or monetary compensation. Participants had a mean age of 21.83 (range: 19-27). Six were male; eighteen were female. All of the participants were right-handed (as assessed by the Edinburgh Inventory (Oldfield, 1971)), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Nine participants reported having a left-handed parent or sibling.

3.4.2 Stimuli and design

Strings of five ¥ symbols served as stimuli. The possible target symbols were $\triangle$, $\diamond$, †, or ψ, and on any given trial one of these replaced one of the ¥ symbols (See an example in Figure 3.1B). For half the subjects, $\triangle$ and $\diamond$ served as targets in separate sessions (one in each block); † and ψ served as distractors in both sessions. For the other half, † and ψ, were targets and $\triangle$ and $\diamond$ were distractors. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix. The strings were randomly divided into 25 conditions as a function of their presentation relative to fixation (fixation location) and as a function of target symbol location within the string (target symbol location). Each string was repeated 10 times in each block. Overall, 750 trials per block were distributed across 5 runs of 150 trials each (See Table 3.1, Appendix B).

3.4.3 Procedure

Participants performed a target symbol discrimination task (Figure 3.1B, as paralleling to the target letter discrimination task in Experiment 1). A trial began with a fixation "+" flashed at the center of the computer screen for 500 msec. Once the fixation disappeared, a string of ¥ symbols was displayed for 20 msec. The string was followed by a blank screen for until the participant made their response. Participants were asked to indicate whether or not a target symbol was embedded in the string by pressing "Yes" or "No" response keys as quick and as accurate as possible. For half of the participants, the "Yes" key were assigned to their right hand. For the other half, their left hand was assigned to press "No" key. After the response had been made, a blank screen followed for 480ms, after which the next trial appeared. Figure 3.1A displays a trial sequence. The experiment contained two blocks. In each block, participants pressed a button to discriminate the target character from among two possible distractors. Participants were given a short break after every run, around every seven minutes.

3.4.4 Data Analysis

Analyses were identical to that for Experiment 1 with non-word letter strings, including two-way Analyses of variance (ANOVAs) with fixation position and target location, linear trend analyses with fixation position and target locations, and Point-to-Point Distance method for visual field asymmetry.

Analyses of variance (ANOVAs). ANOVAs were conducted with five levels of fixation position (the center of a string was -2 to 2 symbols away from fixation; the negative value indicated that the string was presented to the left of fixation) and five levels of target position. Significant effects were followed up with the Tukey's post-hoc analyses for the paired comparisons.

Linear trend analyses with fixation position and target location. Linear trend analyses on fixation and linear trend analyses on target location were conducted. On the same logic as Experiment 1, viewing position effect for the non-letter symbol strings would be expected to demonstrate a significant linear trend with fixation position. The linear trend of target location would not be expected given we found a null effect with non-word materials in Experiment 1.

Point-to-Point Distance method for visual field asymmetry. Point-to-point distance method (B. D. Ripley, 1976; B. Ripley, 1979; B. D. Ripley, 1981) was used to quantify the recognition asymmetry between the two visual fields. The same distance function that in Experiment 1 was applied to the current analysis (See Equation 2.1). The dataset with two extreme fixation positions only and that containing all position fixation positions were both analyzed.

3.5 Results

Analyses of variance (ANOVAs). The effect of fixation position is highly significant (Accuracy: F (4, 92) = 16.63, $p < 0.0001$; RTs: F (4, 92) = 13.64, $p < 0.0001$). Tukey post-hoc analysis shows that recognition accuracy is significantly lower when fixation position is at the string's end than any other viewing position, indicating that the function relating to fixation position to recognition is asymmetric (See Figure 3.2). The main effect of target symbol position is significant for accuracy but not for RTs (Accuracy: F (4, 92) = 5.82, $p < 0.0005$; RTs: $p > 0.1$). Tukey post-hoc analysis on target location, however, does not show significant accuracy differences between any two positions (See Figure 3.2). There is a significant interaction between fixation position and target position (Accuracy: F (16, 368) = 9.33, $p < 0.0001$; RTs: F (16, 368) = 4.67, $p < 0.0001$). Multiple comparison tests show that both accuracy and RTs of fixations at the end of the string are significantly lower than other fixation positions when the target is in the first half of the string (1-3 out of 5). This result can be better visualized with Figure 3.4, which plots recognition probability as a function of fixation position for each curve based on the target at a certain position. For targets positioned in the first half of the string, there is the typical asymmetric viewing position pattern, the beginning vs end VP asymmetry, with better performance for a fixation at the beginning character of a string. By contrast, for the targets positioned at the 4th or 5th symbol locations, the pattern is relatively symmetric and is dominated by visual acuity (i.e. a small processing benefit fixating at the center of the string). Figure 3.5 plots recognition probability as a function of the target position relative to fixation. Recognition accuracy is mostly dominated by target distance from fixation, more so for targets in the LVF than in the RVF, while the drop-offs from fixation is smaller for targets at the first or last position within a string.

Linear and quadratic trend analyses with fixation position and target location. Recognition probability averaged over all possible target position varies as a function of initial fixation position with significant linear (Accuracy: $t\ (95) = 2.58$, $p < 0.0001$; RTs: $p > 0.50$) and quadratic trends (Accuracy: $t\ (95) = -5.12$, $p < 0.0001$; RTs: $t\ (95) = 9.02$, $p < 0.0001$) (See Figure 3.2). Target position, on the other hand, shows no significant linear trend (Accuracy: $p > 0.50$; RTs: $p > 0.05$), but does show a significant quadratic trend (Accuracy: $t\ (95) = -7.37$, $p < 0.0001$; RTs: $t\ (95) = -2.17$, $p < 0.005$) (See Figure 3.3).

Similarity measure between the two visual fields: point-to-point distance. *Fixations on the first or last character of string only.* The subset of data included in this analysis is displayed in Figure 3.6. The similarity measure demonstrates a reliable visual field asymmetry. For both recognition accuracy and reaction times, there is a significant dissimilarity between targets presented in the left and right visual fields (Accuracy: $t\ (23) = 3.80$, $p < 0.001$; RTs: $t\ (23) = 1.89$, $p < 0.05$) (For comparisons of similarity measure across experiments, see Figure 3.14).

Similarity measure between the two visual fields: point-to-point distance. *All possible fixation positions across visual fields.* Overall pattern of character recognition for the entire dataset included in this analysis is displayed in Figure 3.7. It shows visual field asymmetry - a significant dissimilarity between the two visual fields with recognition accuracy and reaction times (Accuracy: $t\ (23) = 2.98$, $p < 0.005$; RTs: $t\ (23) = 2.26$, $p < 0.05$)(For comparisons of similarity measure across experiments, see Figure 3.15.).

Summary of Main Results

Non-letter symbol strings demonstrate results parallel to non-word letter strings. There is the beginning vs end VP asymmetry in which initially fixating the beginning of a non-letter symbol string yields better recognition (faster in RTs and higher in accuracy) than fixating the end of a string. Additionally, there is no linear trend for target position within a non-letter symbol string. Most importantly, a similarity measure between the two visual fields reveals RVF superiority in non-letter symbol recognition - as shown for letter recognition (in Experiment 1). The results of non-letter symbol strings (in Experiment 2) parallel those of non-word letter strings (in Experiment 1), suggesting that whatever reliable effects (especially in letter recognition asymmetries between the two visual fields) are obtained, they do not seem to be specific to letter processing by the brain.

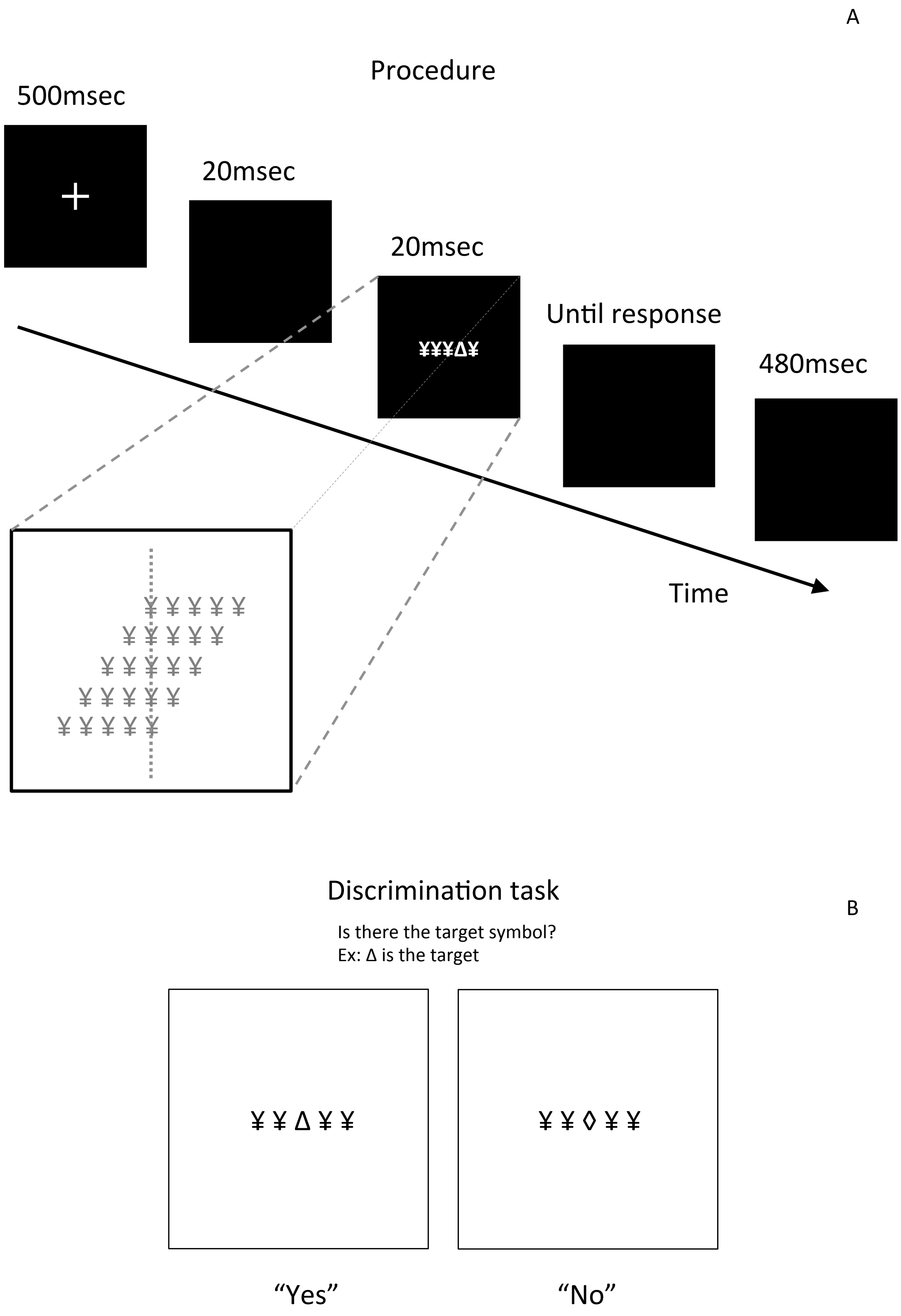

Figure 3.1: Procedure and task. A: procedure for a single trial in viewing position paradigm. B: Example of symbol discrimination task used in Experiment 2.

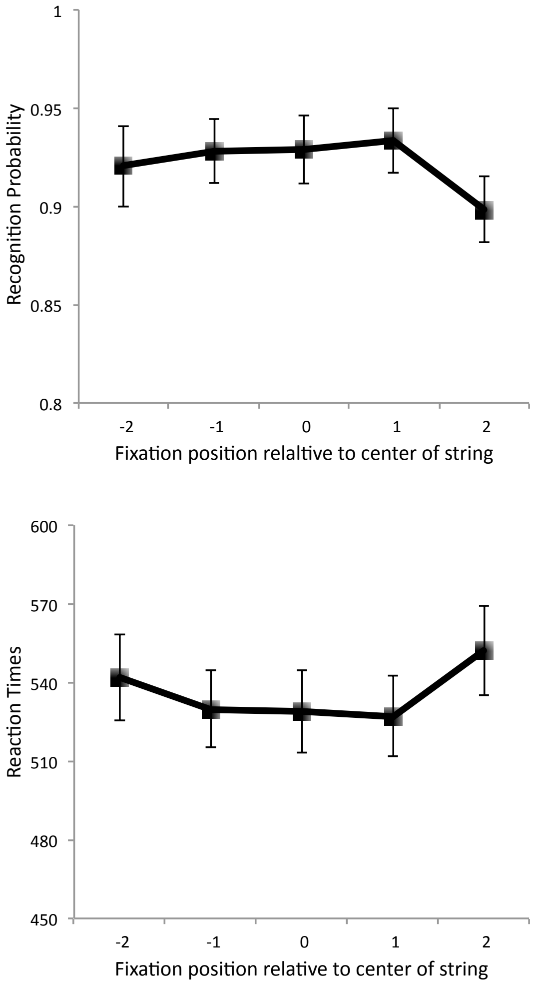

Figure 3.2: Two VP curves for recognition accuracy and speed for non-letter symbol strings. Note the asymmetric beginning vs end viewing position effect for non-letter symbol strings: symbol recognition is more accurate and faster when eyes initially fixate the beginning of a non-word letter string. Top panel, character recognition as a function of fixation position collapsed over target positions. Bottom panel, recognition times for correct character recognition as a function of fixation position collapsed across target positions.

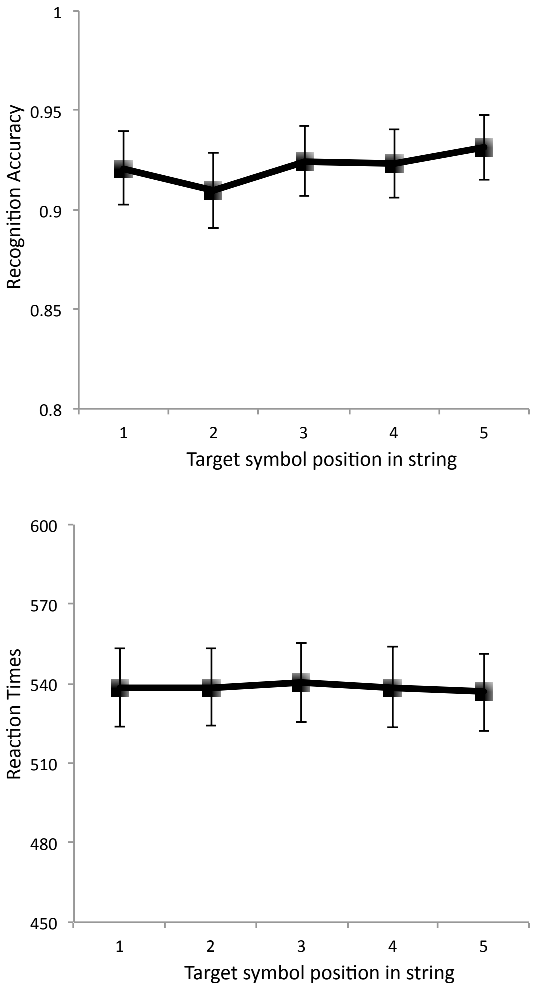

Figure 3.3: Target symbol position function for non-letter symbol strings. Quadratic but no linear trends suggest recognition benefits for the two extreme target locations; no initial symbol benefit is found. Top panel, character recognition probability as a function of target position, collapsed across fixation positions. Bottom panel, reaction times of correct character recognition as a function of target position, collapsed across fixation positions.

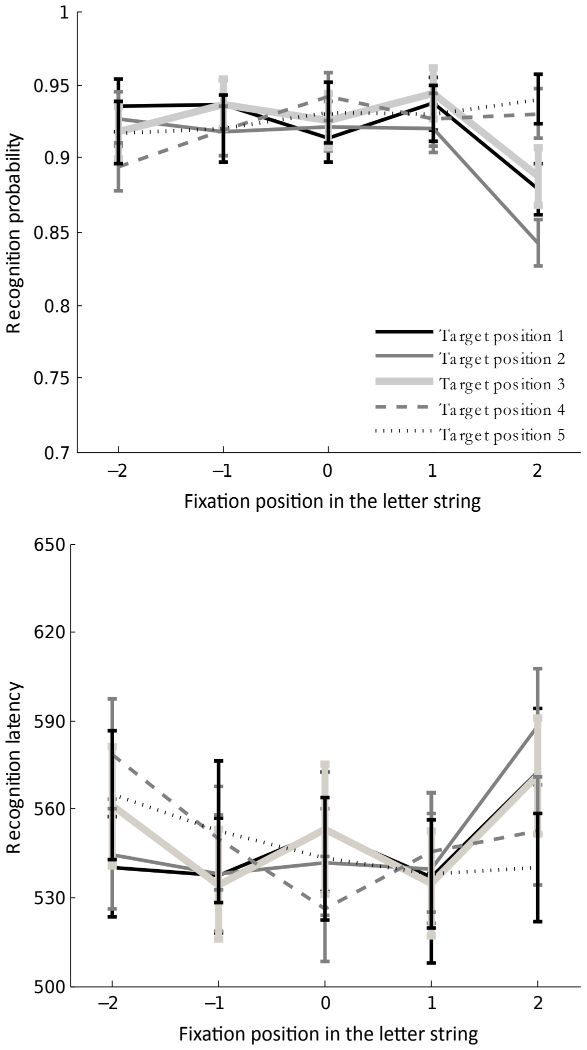

Figure 3.4: Superimposed recognition curves for each target symbol position in non-letter symbol strings. VP curve asymmetries are more pronounced for target symbol positions in the first than second half of a string. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

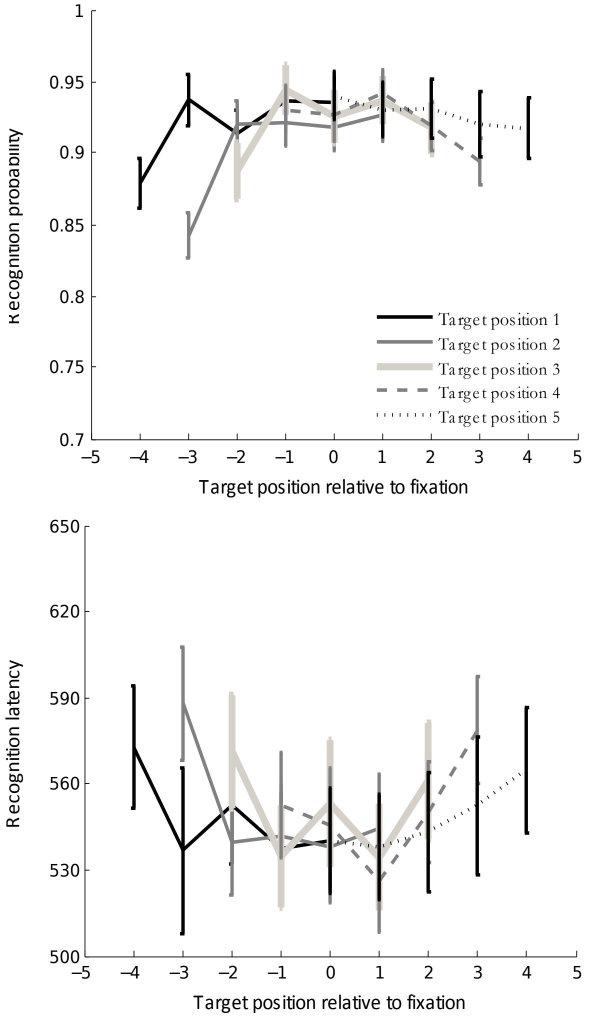

Figure 3.5: Superimposed recognition curves as a function of target distance from fixation for non-letter symbol strings. Recognition performance declines as a function of target symbol distance from fixation, more so in the LVF than RVF. This visual difference contributes to the asymmetric viewing position curves seen for targets in the first vs second half of a string. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

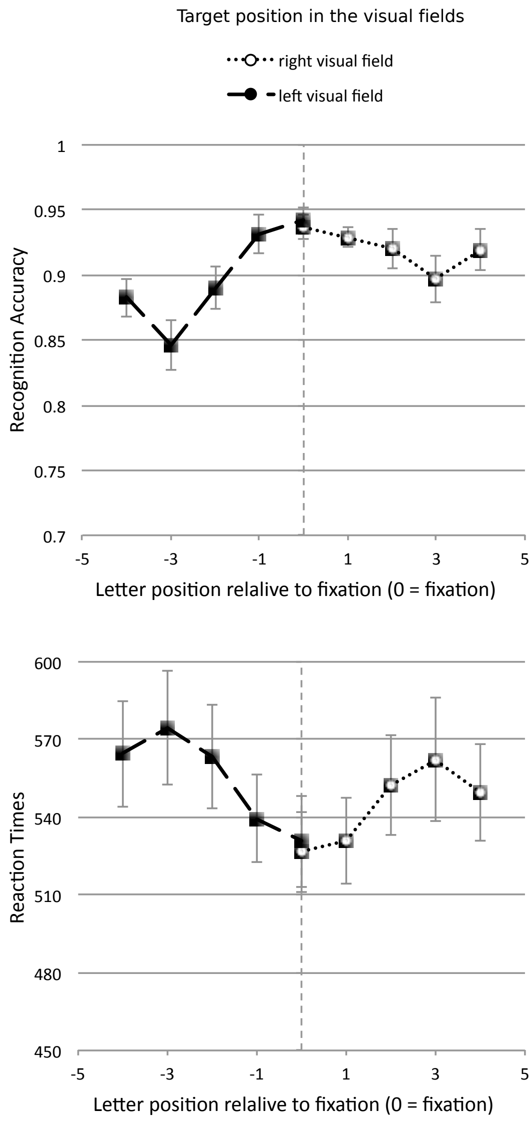

Figure 3.6: Recognition as a function of target distance from fixation for non-letter symbol strings. Recognition of targets in symbol strings presented in the either LVF or RVF. Recognition performance declines as a target moves away from fixation, more so in the LVF than RVF. Top panel, accuracy of character recognition as a function of target distance from fixation. Bottom panel, reaction times of correct character recognition as a function of target distance from fixation.

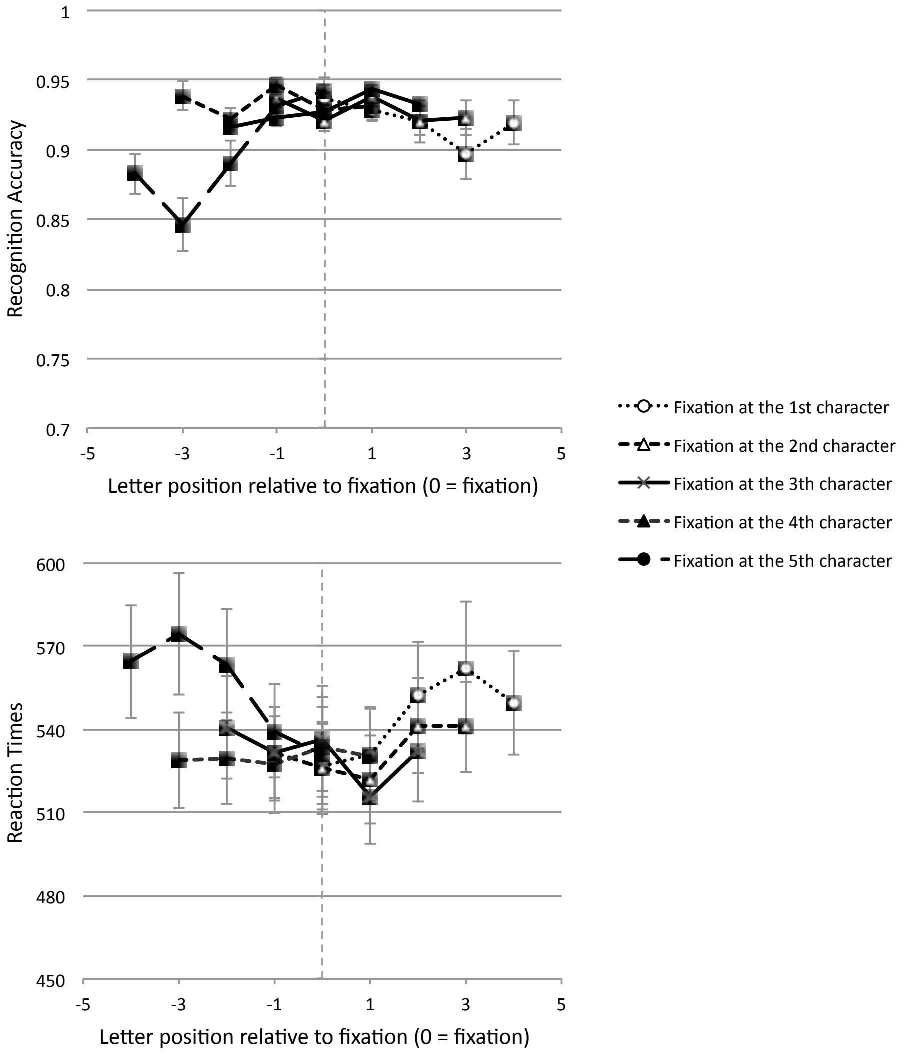

Figure 3.7: Function of target distance from fixation for non-letter symbol strings: fixations at all possible symbol positions in a string. Data points include all fixation positions - fixation on the first character (the rest of characters being in the right visual field - RVF), fixation on the 2nd character, fixation on the 3rd character, fixation on the 4th character, fixation on the last character (the rest of characters are in the left visual field - LVF). Top panel, character recognition accuracy as a function of target distance from fixation. Top panel, accuracy of character recognition as a function of target distance from fixation. Bottom panel, reaction times for correct character recognition as a function of target distance from fixation.

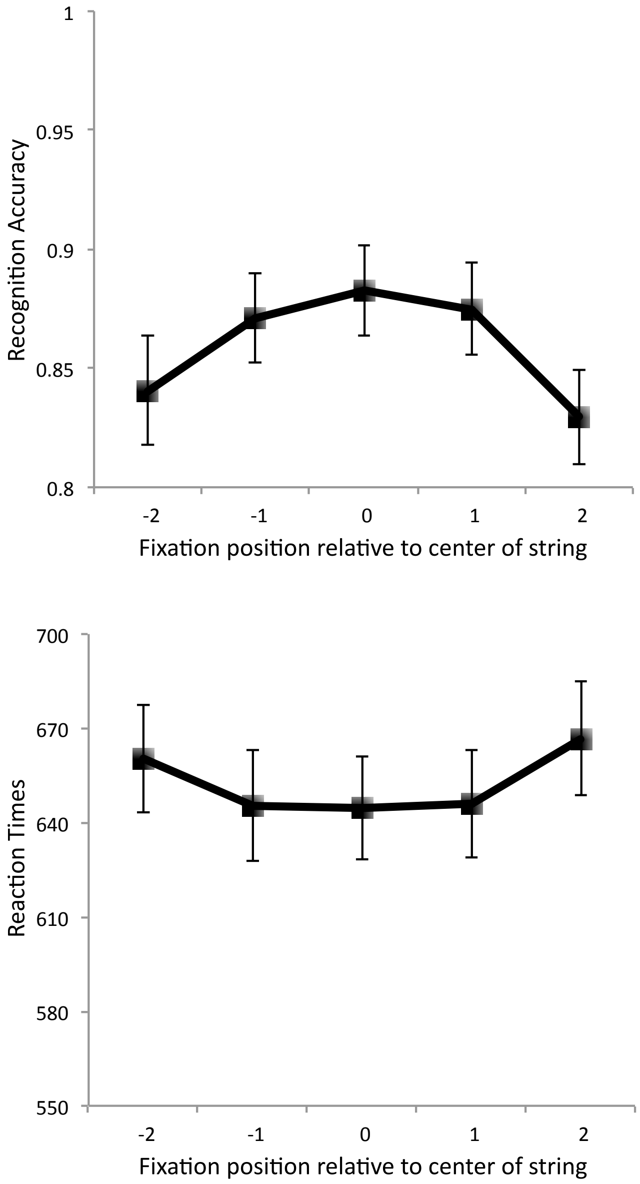

Figure 3.8: Two VP curves for recognition accuracy and speed for non-linguistic ring sequences. Character recognition is equivalently accurate and faster when the eyes initially fixate at the two extremes of a sequence, there is no asymmetric beginning vs end viewing position effect for non-linguistic ring sequences. Top panel, character recognition as a function of fixation position collapsed over target positions. Bottom panel, recognition times for correct character recognition as a function of fixation position collapsed across target positions.

3.6 Experiment 3: Character Recognition in a Non-linguistic Ring Sequence

The goal of Experiment 3 was to determine whether non-linguistic ring sequences are treated by the brain similarly to non-word letter strings and non-letter symbol strings. This is an especially critical point with regard to the beginning vs end VP asymmetry as explained by a perceptual learning account, as it depends on this outcome which may or may not be associated with the stimulus-specific perceptual tuning of written materials. To the extent that non-word letter and non-letter symbol strings yield similar beginning vs end VP asymmetry, we can conclude that the beginning vs end VP asymmetry is not specific to letters, consistent with the hypothesis about perceptual tuning due to perceptual learning while acquiring reading skills for the particular visual configurations used in reading.

An open question, though, is the extent to which recognition for visual stimuli in general will demonstrate an asymmetric VP effect - the beginning vs end VP asymmetry, as observed with strings of non-word letters (in Experiment 1) and strings of non-letter symbols (in Experiment 2). It has been shown that the degree of stimulus difficulty in a perceptual learning task may be a key component that determines the degree of stimulus-specific behavioral improvement. Based on this, we hypothesize that the beginning v end VP asymmetry - the location preferential effect for the specific stimulus trained via perceptual learning (during reading) - will not generalize to simple visual configurations. Specifically, for non-linguistic ring sequences that consist of simple visual characters (Landolt Cs) varying only in visual orientation, and cannot be distinguished by letter-like features, we expect neither the beginning vs end VP asymmetry nor RVF superiority for character recognition in ring sequences.

3.7 Method

3.7.1 Participants

Twenty-four students from the UCSD social sciences undergraduate subject pool participated in the experiment for either course credit or monetary compensation. Participants had a mean age of 21.04 (range: 18-23). Seven were male; seventeen were female. All of them were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Twelve participants reported having left-handed parent or sibling.

3.7.2 Stimuli and design

Non-linguistic ring (Landolt Cs) sequences were used as stimuli. Five characters that were horizontally arranged in an array consisting of four characters with a gap on the bottom and one target character. There were four types of target characters defined by the orientation of their gap - upper left, upper right, lower left and lower right. Half of the subjects were looking for a target character a gap in the upper right or lower right in separate sessions (one in each block); two other types of character with lower gaps were used as distractors. For the other half, targets and distractors were interchanged. Each individual participant was assigned target characters that contained either a right or a left gap in two successive sessions. The assignment of the same left/right targets in two sessions for an individual participant was meant to minimize unintended performance errors due to confusions to participants. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix. The strings were randomly divided into 25 conditions as a function of their presentation relative to fixation (fixation location) and as a function of target position within the string (target position). Each string was repeated 10 times in each block. Overall, 750 trials per block were distributed across 5 runs of 150 trials each.

3.7.3 Procedure

Participants performed the character discrimination task. In all other aspects, the design was identical to that for Experiment 2.

3.7.4 Data Analysis

Analyses were identical to that for Experiment 2 with non-letter symbol strings, including two-way Analyses of variance (ANOVAs) with fixation position and target location, linear trend analyses with fixation position and target location, and Point-to-Point Distance method for visual field asymmetry.

3.8 Results

Analyses of variance (ANOVAs). ANOVAs were conducted with fixation position and target character position. The effect of fixation position is highly significant (Accuracy: F (4,92) = 26.70, $p < 0.0001$; RTs: F (4, 92) = 5.79, $p < 0.0001$). Turkey post-hoc analysis shows that the contribution of differences between fixation positions are from relatively lower performance while fixating the end of the sequence and higher performance while fixating the center of the sequence. The performance difference between fixating at the first character versus the last character is not significant (See Figure 3.8). The main effect of target character position is also significant but only for accuracy (F (4, 92) = 3.62, $p < 0.01$; RTs: $p > 0.1$). Tukey post-hoc analysis, however, do not show significant differences between any two target positions (See Figure 3.9). There is a significant interaction between fixation position and target character position (Accuracy: F (16, 368) = 24.79, $p < 0.0001$; RTs: F (16, 368) = 6.57, $p < 0.0001$). Multiple comparison tests show higher recognition performance on target characters in the first half of a sequence when fixating the first half of the sequence and lower recognition performance when fixating the second half of the sequence and vice versa for the target in the second half of the sequence. The results suggest that the overall patterns of fixation positions and target character positions depend on the distance of the target character from fixation (See Figure 3.10 and Figure 3.11).

Linear and quadratic trend analyses with fixation position and target location. Recognition averaged over all possible target character position varies as a function of initial fixation position with a no significant linear trend (both Accuracy and RTs: $p > 0.1$) but a significant quadratic trend (Accuracy: t (95) = -9.88, p

< 0.0001; RTs: t (95) = 6.63, $p < 0.0001$) (See Figure 3.8). Target position reveals neither a significant linear trend (Accuracy: $p > 0.50$; RTs: $p > 0.05$) nor a significant quadratic trend (both Accuracy and RTs: $p > 0.1$). See Figure 3.9.

Similarity measure between the two visual fields: point-to-point distance. ***Fixations on the first or last character of string only.*** The subset of data included in this analysis is displayed in Figure 3.12. The similarity measure does not show a significant visual field asymmetry. There is no reliable visual field asymmetry for ring sequences for either recognition accuracy ($p > 0.1$) or reaction times ($p > 0.5$) (For comparisons of similarity measure across experiments, see Figure 3.14)

Similarity measure between the two visual fields: point-to-point distance. ***All possible fixation positions across visual fields.*** Overall pattern of symbol recognition for the entire dataset included in this analysis is displayed in Figure 3.13. There is no reliable visual field asymmetry, however, for ring sequences for either recognition accuracy ($p > 0.05$) or reaction times ($p > 0.05$) (For comparisons of similarity measure across experiments, see Figure 3.15).

Summary of Main Results

Non-linguistic ring sequences do not show the beginning vs end VP asymmetry that has been shown for non-word letter strings and non-letter symbol strings. Instead, there is the VP curve symmetry in which fixating the center of a sequence yields better recognition (faster in RTs and higher in accuracy) than fixating the rest of locations within the sequence: there is no recognition difference between fixating the beginning versus the end of a sequence. Consistently, the similarity measure between the two visual fields reveals no evidence of processing superiority in character recognition for either of the visual fields. The only finding parallel to what has been seen for letters and symbols is a null effect of initial target benefit.

There is no beginning vs end VP asymmetry on character recognition accuracy for non-linguistic ring sequences. The observed beginning vs end VP symmetry with non-word letter strings (in Experiment 1) and non-letter symbol strings (Experiment 2) were not obtained with non-linguistic ring sequences (in Experiment 3). The recognition accuracy function of fixation position shows a symmetric drop-off from the center of the sequence, regardless of the visual field of target presentation. Experiment 3 demonstrates a typical distance-from-fixation effect: recognition accuracy decreases as the target position moves from fixation, presumably due to visual acuity drop-off outside the center of fixation. The initial fixation position and the target position within the sequence play minimal roles on patterns of the viewing position pattern for non-linguistic ring sequences, suggesting the beginning vs end VP asymmetry does not generalized to visual processing in general.

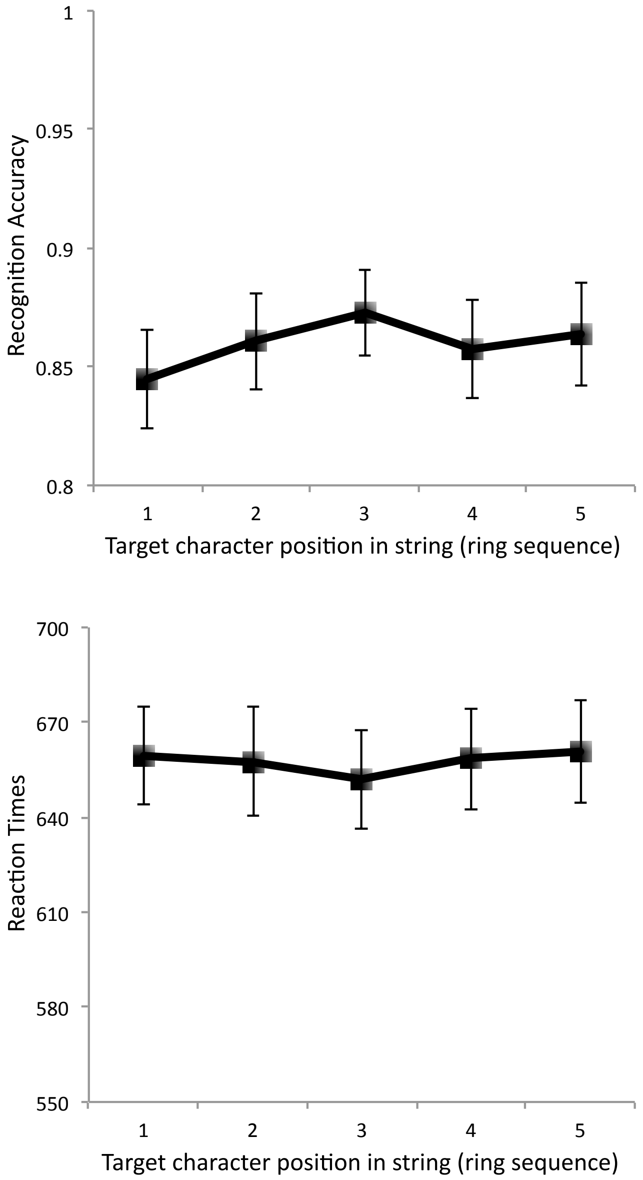

Figure 3.9: Target character position function for non-linguistic ring sequences. Neither linear nor quadratic trend over target character locations is found. Top panel, character recognition probability as a function of target character position, collapsed across fixation positions. Bottom panel, reaction times for correct character recognition as a function of target letter position, collapsed across fixation positions.

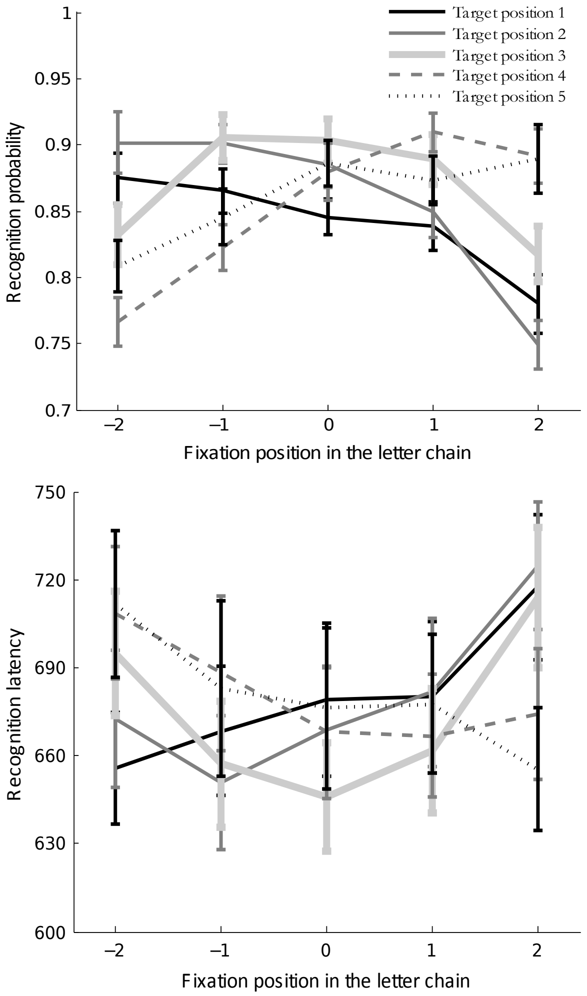

Figure 3.10: Superimposed recognition curves for each target symbol position in non-linguistic ring sequences. A left-ward asymmetric VP curve is for target positions at the beginning of a sequence while t a right-ward asymmetric VP is for target positions at the end of a sequence. The VP patterns for given target position in a sequence are mainly determined by target's distance from fixation: across all target positions in a sequence, recognition performance is always better for targets that are near fixation. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

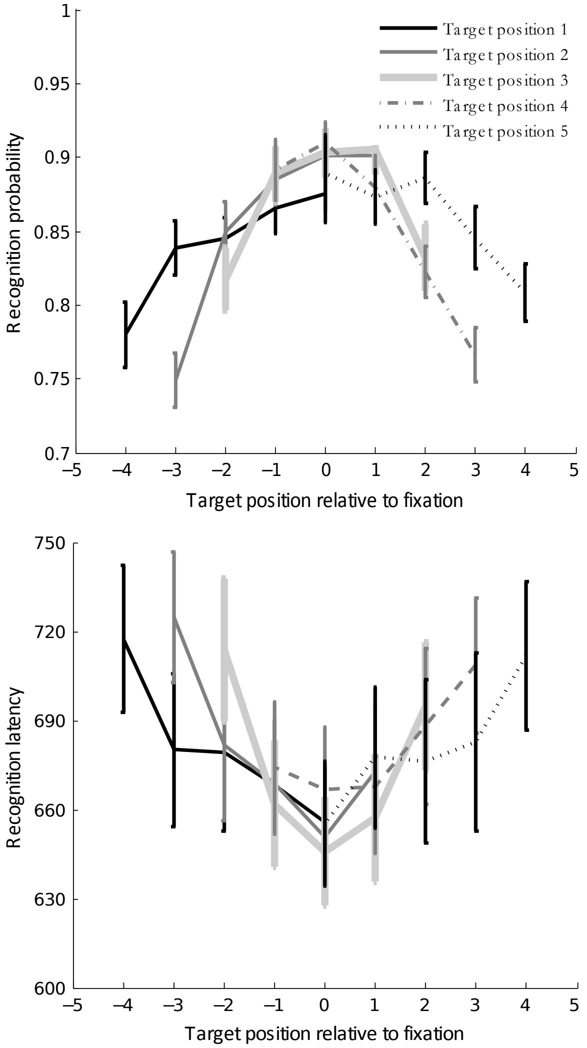

Figure 3.11: Superimposed recognition curves as a function of target distance from fixation for non-linguistic ring sequences. Recognition performance declines as a function of target character distance from fixation, similarly for both targets in the LVF and RVF. Top panel, recognition accuracy. Bottom panel, reaction times for correct character recognition.

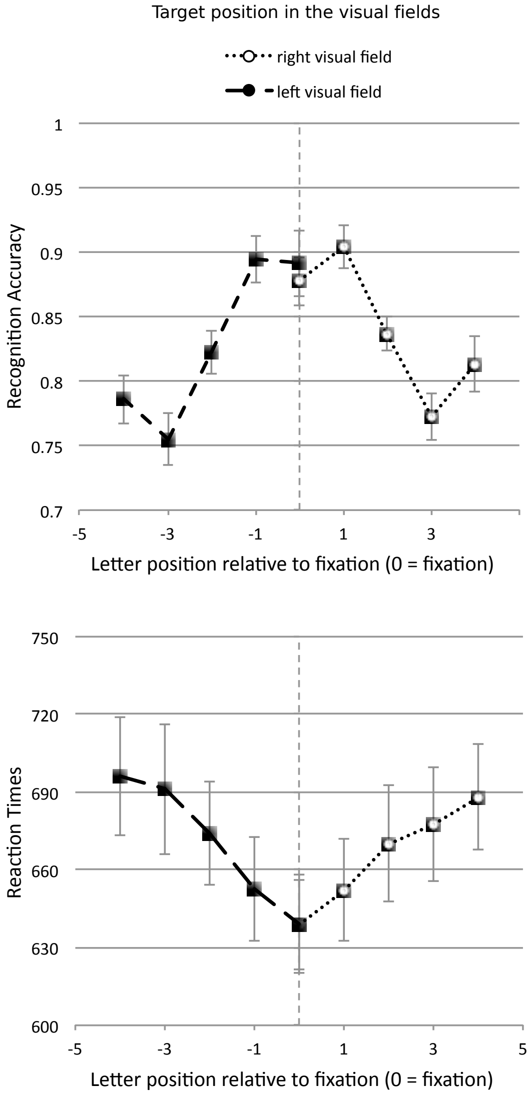

Figure 3.12: Recognition as a function of target distance from fixation for non-linguistic ring sequences. Recognition of targets in ring sequences presented in the either LVF or RVF. Recognition performance declines as a target moves away from fixation, equivalently for in the LVF and in the RVF. Top panel, recognition accuracy as a function of target distance from fixation. Bottom panel, reaction times of correct character recognition as a function of target distance from fixation.

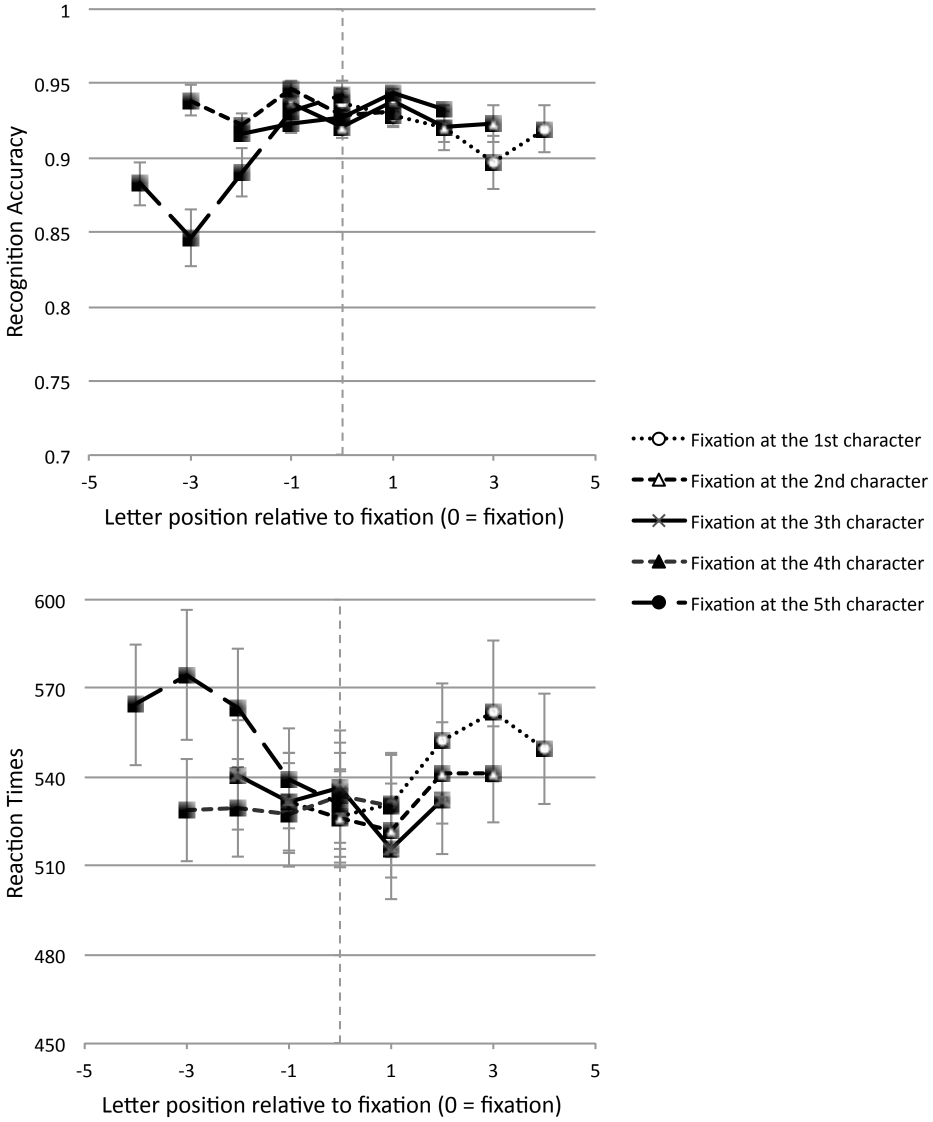

Figure 3.13: Function of target distance from fixation for non-linguistic series of rings. Data points include all fixation positions - fixation on the first character (the rest of characters being in the right visual field - RVF), fixation on the 2nd character, fixation on the 3rd character, fixation on the 4th character, fixation on the last character (the rest of characters are in the left visual field - LVF). Top panel, character recognition accuracy as a function of target distance from fixation. Top panel, accuracy of character recognition as a function of target distance from fixation. Bottom panel, reaction times for correct character recognition as a function of target distance from fixation.

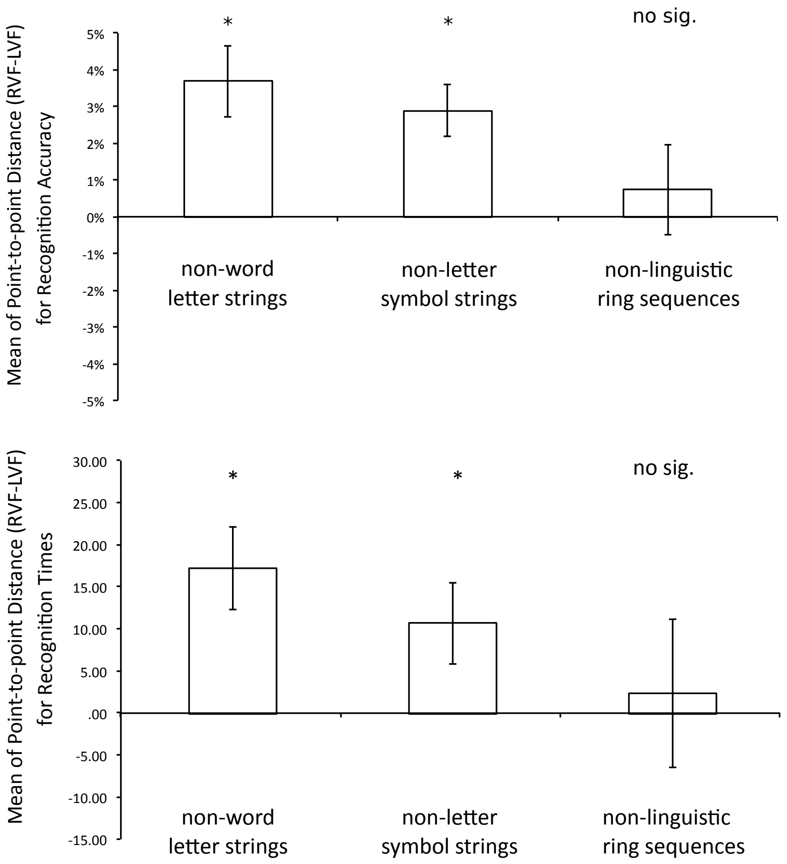

Figure 3.14: Similarity measure between visual fields for three types of stimulus strings (Experiment 2 and Experiment 3 of the current study, as well as Experiment 1 from the previous chapter). Data are from fixations to the two extreme letters. Both non-word letter strings and non-letter symbol strings show RVF recognition superiority. By contrast, non-linguistic ring strings do not demonstrate recognition asymmetry, nor a superiority effect in either visual field. Top panel, recognition accuracy. Bottom panel, reaction times. Note that positive values indicate RVF superiority while negative values indicate LVF superiority.

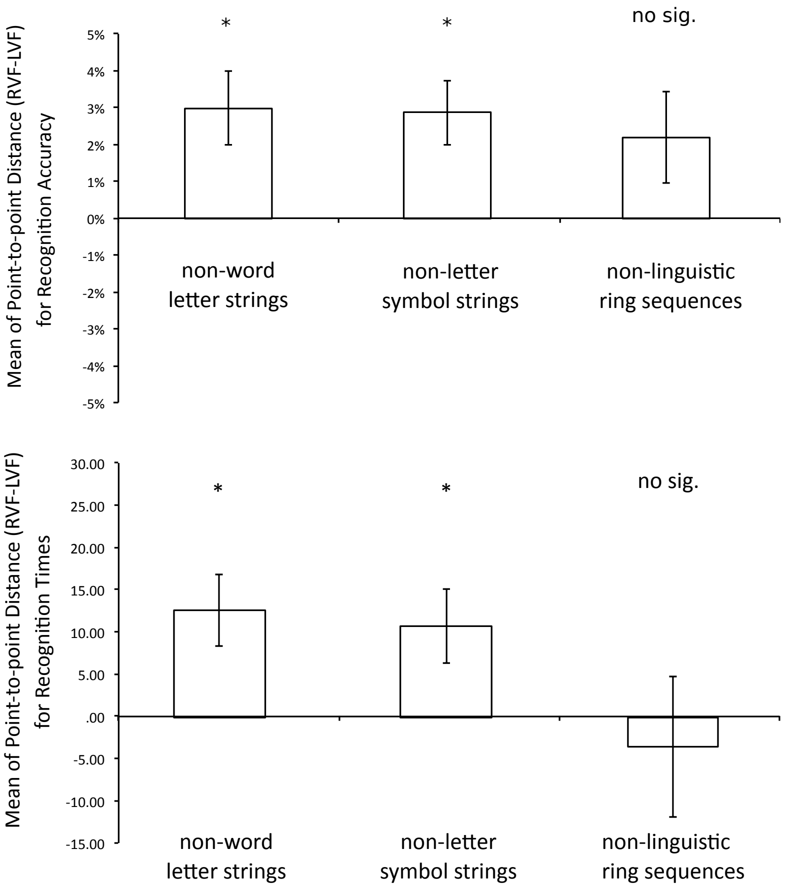

Figure 3.15: Similarity measure between visual fields for three types of stimuli (Experiment 2 and Experiment 3 in the current study, as well as Experiment 1 from the previous chapter). All data points are included. Both non-word letter strings and non-letter symbol strings show RVF recognition superiority. By contrast, strings of non-linguistic ring sequences demonstrate no recognition asymmetry, nor a superiority effect in either visual field. Top panel, recognition accuracy. Bottom panel, recognition reaction times. Note that positive values indicate RVF superiority while negative values indicate LVF superiority.

3.9 Discussion

The primary goal of this study was to examine the extent to which perceptual learning shapes the visual asymmetry in a viewing position paradigm. The perceptual learning account of the VP curve asymmetry hypothesizes that the location preferential tuning as reflected by RVF superiority in letter recognition is limited to the types of stimuli that are perceptually trained during reading. Although it has been suggested that perceptual experience of reading modulates the VP curve asymmetry, evidence for stimulus-specificity in perceptual learning during reading has been based on the comparison of effects between reading experiences that may reside in changes of higher-level representations. For example, (1) the VP curve asymmetry is more pronounced for visually familiar words compared to visually unfamiliar nonwords (Nazir et al., 2004), (2) the direction of the preferential location effect depends on reading direction (Nazir et al., 2004), and (3) non-specific training (to various stimulus in the training sessions) results in no behavioral improvement (Huckauf & Nazir, 2007). To our knowledge, none of studies, however, provides evidence that directly demonstrates that the extent to which superior recognition performance for visual stimuli in the RVF is specific to the stimuli that are perceptually trained during reading. Thus, it is not clear whether or not "the trained stimuli" are restricted to letters. The present study was designed for an examination on the stimulus-specificity of perceptual asymmetry, for non-letter symbol strings and for non-linguistic ring sequences. Following the design in Experiment 1, we employed a viewing position paradigm, in which participants made a target discrimination to horizontally arranged non-letter symbol strings (Experiment 2) and non-linguistic ring sequences (Experiment 3) that were presented randomly spanning around fixation.

We observed an asymmetric VP curve - the beginning vs end VP asymmetry - with non-letter symbol strings. The average recognition accuracy is better when initial fixation is on the first letter of string than the last. If location preferential perceptual tuning due to learning to read are limited to letter recognition, then no beginning vs end VP asymmetry is expected for non-letter symbol materials. However, this was not what we observed. The beginning vs end VP asymmetry for non-letter symbol strings suggests similar perceptual tuning due to reading may contribute to symbol recognition and underly the processing preference for initial fixation position as reflected in the beginning vs end VP asymmetry for non-word letter strings. This is consistent with a view on which letters and symbols share similar visual configurations used by human written system (Szwed et al., 2011). Moreover, processing specificity due to perceptual learning during reading also plays a critical role in brain imaging studies of visual word recognition; it is known as the perceptual expertise hypothesis on visual word form: the visual word recognition (on its specialized processing dynamics and specialized brain regions) arises from perceptual learning mechanisms (McCandliss, Cohen, & Dehaene, 2003). Although it is still a matter of debate, whether perceptual learning specificity - for words and letter strings - should be treated as a “visual word form modularity”, across materials, studies have shown enhanced activations to words and symbols relative to control visual scrambles

By contrast, for non-linguistic ring sequences, we observed a symmetric VP curve: there was no beginning vs end VP asymmetry. This does not indicate better recognition performance when the eyes initially fixate the beginning of a non-linguistic ring sequence. Given that the non-linguistic ring sequences are visually simpler configurations compared to the non-letter symbol strings used in Experiment

2, a symmetric VP curve is consistent with the above view that effects of perceptual learning during reading is constrained to the stimuli that share visual configurations with letters.

With respect to the impact of perceptual learning on the VP curve, the VP asymmetry reflects the combinatory effects, the effects of both stimulus-specificity and location-specificity on perceptual learning. On the one hand, the asymmetry, according to the perceptual learning account, is the result of a frequency-sensitive training mechanism with a PLP during normal reading, reflecting the behavioral improvement of perceptual learning at specific trained locations in visual space. On the other hand, the asymmetric VP pattern should be specific to stimuli that are perceptually trained during reading. If learning to reading provides a context of perceptual learning for letter-like visual configurations that are characteristic of the written system, as we have shown, then the VP curve asymmetry, which exhibits the location specificity for better performance while the eyes fixate the beginning of a string, would not be obtain with non-linguistic ring sequences. This was what we observed: an asymmetric VP curve for complex non-letter symbol strings and a symmetric VP curves for simple non-linguistic ring sequences. Moreover, previous studies have consistently shown the location-specificity of perceptual learning for complex pattern recognition, while the effects for simple orientation features could be transferred to locations in visual space that were not perceptually trained. If, however, recognition on simple feature orientation is indeed perpetually trained during reading, it may not demonstrate any location preference but there may be, nonetheless, behavioral improvements for character orientation recognition more generally. Generalization of the perceptual learning effect to untrained visual space in the contralateral visual field (Liu, 1995; Ding, Song, Fan, Qu, & Chen, 2003; Liu & Weinshall, 2000) could contribute to the symmetric VP pattern for character orientation task for non-linguistic ring sequences. The distinction between the two stimulus types, non-letter symbol strings and non-linguistic ring sequences, also reconciles with previous studies on the dependence between the complexity of perceptual learning and the location specificity.

Neither non-letter symbol strings nor non-linguistic ring sequences demonstrated the target initial benefit: recognition on the target positioned at the beginning of a string or a sequence was not superior compared to recognition for a target at the end in a string. Taken together with the distinction of the beginning vs end VP asymmetry between two types of stimuli, we show that the VP curve is dissociable from the initial target benefit, consistent with what we found with non-word letter strings in Chapter 2.

Finally and critically, there was superior symbol recognition in the RVF than LVF; recognition of ring character orientation, however, showed no visual field difference. This is consistent with the prediction of the perceptual learning account for the VP curve asymmetry on perceptual asymmetry. That is, whether the VP curve is asymmetric or not depends on whether or not there is recognition asymmetry between the two visual fields. For words, the perceptual learning account posits that the VP curve asymmetry could be attributed to RVF superiority for letter recognition, suggesting recognition asymmetry underlies the VP curve asymmetry. If this is the case, then the concurrence of VP curve asymmetry and recognition asymmetry between visual fields is expected. Likewise, we would expect the absence of recognition asymmetry in response to stimuli that do not show the VP curve asymmetry. Our results, as predicted, thus provide consistent data on the impact of superior recognition in the RVF on the beginning vs end VP asymmetry.

The recognition asymmetry, for words and letters, as well what we have shown with symbols, according to the perceptual learning account, has been attributed to perceptual tuning of the early visual areas. One might speculate that such an early perceptual tuning might lead to modulations for visual processing in general - it seems to be counter-intuitive that the neural activations in early visual area would selectively respond to complex patterns but exclude the simpler visual features given the simple-to-complex hierarchy of the visual system. I would like to point out that this seeming contradiction between the fact that the perceptual tuning for complex stimuli extends to early visual areas and there is no perceptual asymmetry for simple stimuli could be due to a false inference between the overall hierarchy of functional organization to the level of processing of a specific effect; in contrast, the level of processing (simple versus complex) does not necessarily directly map onto the hierarchy of functional organization (early versus late). Given the limited inferences drawn from the behavioral measures, an inference on the locus of neural mechanisms for simple visual features is limited. Likewise, it is too naive to assume that recognition for simple visual configurations subjects to some hypothetical reductive mechanisms by merely scaling down known mechanisms underlying perceptual learning on complex pattern recognition. The fact that early visual areas are known to represent lower level visual configurations does not confine that the locus of neural mechanism underling perceptual learning for simple feature recognition should be restricted in early visual areas. Even though it is plausible that the early perceptual tuning may lead to neural modulations for visual processing in general, it is not likely to operate such that early visual areas selectively and exclusively activate in response to complex visual configurations (such as non-word letter and symbol strings) but opt not to regard to simple stimuli (such as non-linguistic ring sequences). Instead, in addition to the changes in early visual areas, the potential mechanisms underlying perceptual learning for simple recognition might also involve higher order brain areas.

The alternative that perceptual learning for simple pattern recognition, if exists, may be not location-specific, is consistent with the so-called reverse hierarchy theory of visual perceptual learning proposed (Ahissar & Hochstein, 1997). That is, with complex recognition, perceptual learning is specific to stimulus type and location, matching the fine spatial retinotopic maps in early visual areas; with simple recognition, perceptual learning generalizes across features of stimulus and location in visual space, matching the spatial generalization that occurs in higher visual areas. Explanations countering this intuition focused on the dependence between stimulus-specificity and the difficulty of perceptual learning. There is a bidirectional relationship between the stimulus specificity and stimulus difficulty. In the orientation perceptual training task, increasing training orientation difficulty induces both orientation-specificity (stimulus-specificity) and location-specificity; similarly, increasing training location difficulty induces orientation-specificity (stimulus-specificity) as well (Ahissar & Hochstein, 1997). As noted in introduction, location- and stimulus-specificity have been consistently found in the perceptual learning for complex pattern recognition, implying the neural changes must involve early visual areas (Karni & Sagi, 1991; Ball & Sekuler, 1982; Poggio et al., 1992; Gilbert, Sigman, & Crist, 2001; Berardi & Fiorentini, 1987; Maffei & Fiorentini, 1976; McKEE & Westhe, 1978; Furmanski et al., 2004; Schoups et al., 2001; Schwartz et al., 2002; Crist et al., 2001). By contrast, with respect to perceptual learning for simple orientation recognition, the generalization of learning to untrained locations (i.e. no location specificity) has been suggested to reflect processes involving in higher-level cortical areas (Ahissar & Hochstein, 1997, 2004; Hochstein & Ahissar, 2002; Ahissar, Nahum, Nelken, & Hochstein, 2009). Psychometric learning functions have been shown to support this reverse hierarchy theory. Ahissar and Hochstein (1997) argued that if the improvement due to perceptual learning on complex and simple recognition both rise right after learning, then it is expected that psychometric learning curves (changing with stimulus difficulty) would proceed in parallel with learning sessions. However, that was not what they found. Instead, they found different rising phases (through learning sessions) depending on the difficulty of the stimulus trained via perceptual learning. In the early learning phase, behavioral improvements emerge for the stimuli easy to recognize, which allows generalized to untrained locations and may involve higher order brain areas. In the later learning phase, by contrast, the improvements reflect perceptual learning for difficult conditions, whose location specificity suggests modulations in early areas. Note that what we discussed here, a relationship between location-specificity and visual complexity of pattern recognition, is built upon post-training data (*after* perceptual learning is established). These findings suggest that a location-specificity emerges only with perceptual learning for complex pattern recognition but not with perceptual learning for simple complex pattern recognition *after* perceptual learning has been established. These findings, however, do not imply that a difficult task should exhibit recognition asymmetries spatially *before* perceptual learning has been established; neither do these findings suggest that a simple task should or should not exhibit asymmetries spatially *before* perceptual learning. Following this logic, if the alternative, what we perceptually learn from reading experience is simple visual configurations such as ring characters, is true, we should expect a better recognition performance for ring characters than symbols or letters in general, but do not expect recognition asymmetries (location-specificity) for any of these visual stimulus types. Our data does not support this alternative. The overall recognition performance is worse for ring characters than for symbols or for letters, and recognition for both symbols and letters show location-specificity as evident in the asymmetric VP pattern. It is unlikely a case that perceptual learning acquired by reading experience is associated with recognition of simple visual pattern, such as the ring character we used in Experiment 3. Taken together, our findings that overall performance is better for letters/symbols than for ring characters, and the asymmetric VP patterns for letters and symbols are consistent with the perceptual learning account that recognition for letter and letter-like visual configurations may be perceptually learned while acquiring reading skills; this perceptual learning is not generalized to all types of visual configurations.

3.10 Summary and Conclusions

In sum, our findings indicate that the VP curve asymmetry cannot be generalized to all types of visual stimuli. The beginning vs end VP asymmetry, which we have shown with non-word letter strings (Experiment 1) and non-letter symbol strings (Experiment 2), seems to be restricted to stimuli that share visual configurations used by the human written system. Consistent with this, we observe a symmetric VP curve (no beginning vs end VP asymmetry) for non-linguistic ring sequences (Experiment 3). Moreover, the similarity measure between the two visual fields reveal results predicted by the perceptual learning account for the VP curve asymmetry: while there is recognition superiority in the RVF, the VP curve asymmetry emerges, and vice versa for the absence of both effects. As predicted (by the perceptual learning account), symbol recognition is superior in the RVF compared to the LVF while there is no evidence of the visual field asymmetry for ring sequences. Furthermore, stimulus-specific and location-specific mechanisms underlie perceptual learning. Effects contributing to the VP curve asymmetry due to perceptual learning must be specific to the stimuli that are perceptually trained during reading. In addition, given that the location-specificity of the perceptual learning effect depends on the stimulus difficulty, the stimuli that elicit the effect of processing asymmetry in visual space, to some degree, have to be visually complicated. Our design with non-letter symbol strings and non-linguistic ring sequences, which involve in complex linguistic relevant visual configurations and simple feature orientations, respectively, therefore, allows us to examine these specific predictions based on mechanisms underlying perceptual learning. Consequently, the beginning vs end VP asymmetry to non-letter symbol strings and the absence of the beginning vs end VP asymmetry to non-linguistic ring sequences suggest that the combinatory effect of stimulus-specific and location-specific perceptual learning may contribute to the VP asymmetry, specifically the beginning vs end VP asymmetry. Finally, we discuss the possible neural bases underlying the observed VP curve for both types of stimuli - strings of non-letter symbols and non-linguistic ring characters. The stimulus- and location-specificity of perceptual tuning may be due to perceptual learning in early visual areas. The ease with which a stimulus learned via perceptual learning decreases stimulus-specific and location-specific effects; accordingly, the (location) generalization effect for simple pattern recognition has been proposed to reflect neural modulations in the higher order areas. This is consistent with our findings that there is the beginning vs end VP asymmetry for strings of letters and symbols while there is no beginning vs end VP asymmetry for non-linguistic ring sequences: the observed VP asymmetry is indeed tied to the characteristics of perceptual learning - its stimulus-specificity and location-specificity, indicating the contributions of the perceptual learning account to the beginning vs end VP asymmetry.

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3.12 Appendix B

Table 3.1: The number of trials and target symbols for each block used in Experiment 2

First half of subjects						
			# of conditions	# of repetitions	Total # of trials	
Block 1	Target symbol	Δ	25	10	250	750
	Distractors	◊	25	10	250	
		Ψ	25	10	250	
Block 2	Target symbol	†	25	10	250	750
	Distractors	o	25	10	250	
		Ψ	25	10	250	
Second half of subjects						
			# of conditions	# of repetitions	Total # of trials	
Block 1	Target symbol	◊	25	10	250	750
	Distractors	Δ	25	10	250	
		†	25	10	250	
Block 2	Target symbol	Ψ	25	10	250	750
	Distractors	Δ	25	10	250	
		†	25	10	250	

No. of conditions - 5 locations of letter string x 5 positions of target letter within a string

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Chapter 4

Beyond the viewing position curve: visual acuity and crowding in the two visual fields

4.1 Abstract

The presence of an asymmetric beginning vs end VP effect for non-word letter strings (Experiment 1) and non-letter (letter-like) symbol strings (Experiment 2) but not for non-linguistic ring sequences (Experiment 3) is consistent with the perceptual learning account. Accordingly, in the present study we critically examine an explicit model of the perceptual learning account of the asymmetric VP curve effects, namely the Multiplied Letter Identification Processing (MLIP) model (Nazir, O'Regan, & Jacobs, 1991). The MLIP model was developed to demonstrate how the asymmetric VP effects can arise from a steeper visual acuity drop-off in the left visual field (LVF) than in the right visual field (RVF) consequent to perceptual learning. Studies of visual recognition, however, have shown that visual crowding from adjacent characters can account for the majority of the information loss during visual recognition, even more than that due to the drop-off in visual acuity with stimulus eccentricity. Given the literature on general visual recognition, we thus argue that a drop-off in visual

acuity may not be the only factor contributing to the perceptual asymmetry between the two visual fields, and offer visual crowding as a critical factor. To assess this hypothesis, we re-analyze the data in Experiments 1-3. Instead of analyzing the VP curve as canonically measured (average performance for each string location collapsed across all letter positions within a string), we analyze performance for each letter position within each string at each of the string locations; for a 5 letter string at 5 string locations this is a difference between a curve drawn from 5 data points in the former and 25 data points in the latter. In so doing, we can better determine the extent to which the VP curve asymmetry is attributable to visual acuity, crowding, or differences in either across the visual fields. Our results show that both visual acuity and crowding contribute to the observed patterns of character recognition. For letters and symbols, the perceptual asymmetry can be attributed to a larger visual crowding effect in the LVF than in the RVF. Consistent with this explanation, non-linguistic ring sequences do not show a crowding asymmetry across the visual fields.

In Experiment 4, these novel findings regarding crowding (a)symmetry for the different stimulus types were replicated within-subjects. The magnitude of each effect - visual acuity, crowding, and crowding asymmetry for non-word letter strings – is significantly correlated with that for non-letter symbol strings; none are correlated with the effects for non-linguistic ring sequences. The stimulus-specific crowding asymmetry contributions to the VP curve asymmetry suggest a role for perceptual learning in the visual word recognition asymmetry.

4.2 Introduction

A word, as a visual object, consists of component parts – namely, letters; word recognition, as a type of object recognition, requires processes for determining letter identities and the integration of the letters that constitute the word being recognized. The efficiency of visual word recognition, in fact, rests on a reader's ability to accurately recognize letters (Pelli, Farell, & Moore, 2003). Studies have shown that the number of letters in a word that are recognized in parallel determines word reading speed (J. K. O'Regan, 1989; J. O'Regan, 1991; Legge, Mansfield, & Chung, 2001). Visual *word* recognition faces processing challenges similar to those faced by visual *object* recognition with regard to feature detection and combination - identifying component letters and combining them in the correct order (Treisman & Gelade, 1980).

Studies have found that letter recognition is constrained by the amount of visual information available to the visual system (Legge et al., 2001). This together with the linear drop off in visual acuity from fixation means that the bottom-up letter information available to word recognition is characterized by a visual information availability function (J. K. O'Regan, Lévy-Schoen, & Jacobs, 1983). The drop-off in letter recognition from fixation leads to a hypothesis of visual word recognition based on letter visibility across retinal locations relative to fixation. The convenient viewing position (VP) hypothesis, proposed by J. O'Regan, Lévy-Schoen, Pynte, and Brugaillère (1984), describes how initial eye fixation influences word recognition due to the drop-off in visual acuity from fixation: the closer the fixation to the convenient viewing position, the lower the probability that a second fixation on the word will be required for identification. Following the convenient viewing position hypothesis, the summed letter information model (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989) provides a mathematical description of word recognition as a function of the amount of visual information in individual letter locations. Simply by introducing a linear drop-off in visual acuity from fixation as the determinant of the amount of letter visual information available at a given letter location relative to fixation, the summed letter information model generates an overall symmetric U-shaped VP curve as predicted by the convenient viewing position hypothesis. This typical distance-from-fixation effect on the VP curve suggests that visuo-spatial processing may account for visual word recognition in a bottom-up fashion.

The VP curve for visual word recognition, however, raises a question for this account (Warrington & Shallice, 1980; Riesenhuber & Poggio, 1999). Words are recognized faster and more accurately when a reader's eyes initially fixate the beginning than the end of a word, suggesting that the retinal distance of a letter from fixation may not be the only factor determining availability of visual information. On the one hand, the VP curve does show that word recognition depends on the location of component letters, indicating a role for visuo-spatial processing at the front-end of visual word recognition. One the other hand, the finding that the VP curve is asymmetric indicates that a visual word recognition model based solely on the drop-off of visual acuity from fixation may prove inadequate. It is thus likely that top-down information from a word representation or other visual mechanisms may intervene and lead to a preferential processing shift within a word. Moreover, an asymmetric VP curve may implicate an object-centered (word-centered) spatial frame of reference. If visual information availability depended solely on a letter's position relative to fixation, i.e. were based on a retinotopic spatial reference, then the VP curve would be symmetric.

However, the VP curve is asymmetric; given an assumption that visual acuity drops off symmetrically in the two visual fields, this suggests that visual acuity limitations in the human visual system alone (Wertheim, 1894) will not suffice to explain the curve or for that matter word recognition. Using the VP curve as a vehicle to study the variability in information availability across a word may help to explain word recognition, and the extent to which it is a special case of object recognition.

In particular, we ask whether it is possible to explain the asymmetry of the VP curve without assuming a holistic word unit and a word-centered reference. The need for an additional word-centered reference is based on the assumption that the visual acuity drop-off function is symmetric. Some studies, however, have shown that although there is a symmetric decrease with distance from fixation in recognition of isolated letters, there is a right visual field (RVF) superiority in recognition of letters embedded in a letter string (Bouma, 1970; Bouma & Legein, 1977; Loomis, 1978; Legge et al., 2001). Yet, it is not clear empirically how these two factors - (the presumably symmetric) visual acuity drop-off and within-string-letter recognition asymmetry (due to whatever mechanism) can account for the asymmetric VP curve. And, even if there is a coherent explanation, we would ask whether this explanation requires any additional assumption(s) beyond that of a retinotopic representation for processing of visual word form.

A second critical question I believe needs to be addressed is whether the mechanism(s) responsible for the asymmetric VP curve is specific to visual word forms. The trend toward an asymmetric VP curve has been found to emerge as early as the end of first year of schooling, while specialization for visual word form processing seems to take around five years of academic training (Aghababian & Nazir, 2000).

On the other hand, variation in letter information availability within a word may shape this perceptual learning process in visual word recognition (Cohen et al., 2000, 2002; Cohen & Dehaene, 2004; Dehaene, Cohen, Sigman, & Vinckier, 2005; McCandliss, Cohen, & Dehaene, 2003). On the other hand, variation in letter information availability within a word may shape this perceptual learning process in visual word recognition (Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004). Therefore, the same factors that lead to the early emergence of the VP curve asymmetry may also influence the development of perceptual expertise on visual word form processing. As perceptual learning is typically stimulus-specific (Ball & Sekuler, 1987; Karni & Sagi, 1991; Fahle & Morgan, 1996; Westheimer, 1996; Li, Piëch, & Gilbert, 2004; Sigman et al., 2005; Polley, Steinberg, & Merzenich, 2006), if the VP curve arises from perceptual learning mechanisms, then at least some the factors that contribute to the VP curve asymmetry may likewise demonstrate stimulus-specificity. Studies of the VP curve thus should address the role of spatial reference and stimulus-specificity if they are to lead to a better understanding of visual word recognition.

The Multiplied Letter Identification Probability (MLIP) model offers a possible mechanism for the VP asymmetry, without any additional visual spatial reference other than a letter's retinal eccentricity from fixation (Nazir et al., 1991). According to MLIP model, the VP curve asymmetries (the beginning vs end VP asymmetry and left-of-center optimal viewing position (OVP) asymmetry) are due to a steeper drop-off of visual acuity in the left visual field (LVF) than in the right visual field (RVF). This assumption of a visual acuity asymmetry is based on the finding that visual span is wider to the right than left of fixation (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980; Rayner, Well, Pollatsek, & Bertera, 1982). In the

MLIP model, the viewing position curve is estimated by multiplying recognition probability over letters in a word at each given fixation. The letter recognition function is computed based on empirical letter visibility measurements at various eccentricities from fixation when a target letter was embedded in a letter string presented in either the LVF or RVF. A linear function of letter eccentricity is used to fit the decline of letter recognition probability separately in each visual field. Consistent with their visual acuity asymmetry assumption, the absolute value of the slope of the linear letter eccentricity function in the LVF is larger than that in the RVF, indicating a steeper drop-off with visual acuity in the former. In other word, letters falling in the LVF would suffer more dramatic recognition declines with increasing eccentricity compared to letters in the RVF. Therefore, for a word fixated at its end, where the majority of letters are in the LVF, word recognition probability would be lower than for other fixation locations. The VP pattern estimated by the MLIP model is qualitatively similar to the empirical VP curve. It successfully provides a simple visual word model of the VP curve asymmetry based on the visual acuity asymmetry between the two visual fields, without assuming a word-centered reference. The MLIP model's critical assumption that differential visual acuity drop-offs between the hemispheres alone suffices to account for the VP asymmetry, however, requires further scrutiny. There are data indicating that letter recognition is not only limited by acuity but also by visual crowding (Bouma, 1970). Visual crowding is a phenomenon referring to an impaired recognition performance of a visual object due to surrounding visual objects. According to Bouma's law (Bouma, 1970), once the space between the two adjacent objects is smaller than the so-called "critical space", recognition impairment due to visual crowding emerges, and critically this critical space is a function of stimulus eccentricity. Therefore, both visual acuity and visual crowding are functions of stimulus eccentricity from fixation. Acuity is a size limitation, while crowding is a spacing limitation (Song, Levi, & Pelli, 2014). When the size of stimulus is fixed, visual acuity decreases with the stimulus eccentricity (Olzak & Thomas, 1986; McConkie et al., 1989). Likewise, when the space between adjacent objects is held constant, visual crowding increases with stimulus eccentricity (Bouma, 1970, 1973). Independent contributions to recognition performance from visual acuity and visual crowding have been suggested by many studies of visual recognition (Chung, Levi, & Legge, 2001; Intriligator & Cavanagh, 2001; Pelli, Palomares, & Majaj, 2004) (See D. Whitney and Levi (2011) for a review). In short, the smallest readable letter size (acuity) that can be recognized is independent of interference due to the size of the critical space between two adjacent letters (crowding), and vice versa the critical spacing determined by crowding is independent of stimulus size and depends on stimulus eccentricity. Song et al. (2014) further demonstrated different clinical conditions lead to problems with visual acuity and visual crowding, with each selectively impairing one or the other – indicating a double dissociation between the two. Moreover, it has been suggested that the impact of visual crowding on recognition performance may be larger than that of visual acuity. Compared to 6% or so information loss attributable to the decline in visual acuity from fixation, crowding can account for up to 75% of the information loss (Yu, Legge, Wagoner, & Chung, 2014).

Note that the VP curve represents recognition performance as a function of fixation position. Investigations of VP effects focus on recognition of stimuli that span fixation. This is but a subset of the observer's entire visual space – itself a subject of much research on visual perception more generally. As visual crowding is considered an important factor in this general literature on visual recognition, there is no principled reason that VP effects should not likewise be subject to the influence visual crowding. We can, therefore, reasonably ask whether visual crowding need be incorporated into the MLIP model. One reason that the MLIP model has not taken visual crowding into account may be because in the typical experimental procedure used to estimate letter visibility function the number of letters surrounding the target letters is held constant. Moreover, as pointed out by Brysbaert and Nazir (2005)), recognition of the two extreme letters in the periphery - the first letter in the LVF and the last letter in the RVF, are discarded as the outliers in the MLIP model. These "outliers", however, might potentially reflect an impact of crowding - the higher recognition at these two extreme positions might be due to the fact that there was only one adjacent letter in one or the other side. Since the two extreme locations may suffer less crowding from a nearby letter(s), removing them may lead to an underestimation of performance (compared to empirical human performance), and indeed the MLIP model underestimates word recognition performance compared empirical human data.

With respect to the recognition asymmetry, crowding is indeed crucial to consider: studies have shown letter visibility on an isolated letter is the same in the LVF and RVF (Bouma, 1970), while letter recognition probability is higher in the RVF than LVF for letters within strings (Bouma, 1973; Bouma & Legein, 1977; Legge et al., 2001). This suggests that recognition asymmetry may not be (solely) a function of visual acuity asymmetry but perhaps (also) a crowding asymmetry. Not taking crowding into consideration, the MLIP model could suffer the risk of low prediction power.

The relevance of a crowding asymmetry between the LVF and RVF for visual word recognition has recently been addressed in the Modified Receptive Fields (MRF) hypothesis (Tydgat & Grainger, 2009; Grainger, Tydgat, & Isselé, 2010; Chanceaux & Grainger, 2012). The MRF hypothesis relies on visual crowding to explain the word beginning bias – i.e., that initial letters within a word or in a string are better recognized than the letters at its end. Crowding is assumed to be a consequence of the excessive pooling of visual features at a given location with those from nearby locations (Pelli et al., 2004, 2007). According to a general model of crowding (Nandy & Tjan, 2012), the interference due to overlapping integration fields, the so-called crowding zone, increases linearly with eccentricity (Bouma, 1970). Moreover, the shape of crowding zone is hypothesized to be elliptical (Toet & Levi, 1992), the so-called inward-outward crowding shape asymmetry, elongated toward the periphery (Bouma, 1978). Based on this general proposal that the size and shape of the crowding zone determines the information interference, the MRF hypothesis further proposes that the size and shape of crowding zone are stimulus specific: the crowding zone for letters is distinguishable from that for other visual objects. This proposal that crowding is stimulus-specific is based on the different serial position effects observed for letters and other visual objects. While geometric-shaped symbol strings demonstrate monotonic declines in recognition probability away from fixation, letter strings show a W-shape letter recognition function, instead, more so for the first than the last letter position.

According to the MRF hypothesis, the W-shaped letter recognition function is due to a boost in letter recognition at the two extreme letter positions due to release from crowding. Additionally, Grainger et al. (2010) found that flankers (nontarget distractors) located to the left of targets interfered more than flankers on the right; this asymmetry is specific to letters in the LVF. The MRF hypothesis, therefore, proposes letter specific adaptation on a basis of the shape and size of the integration field optimized for the processing of words and letter strings. The size of the integration fields for letters is smaller than those for other visual objects and they are elongated in the direction toward the string's initial position (opposite to reading direction). Moreover, they propose that this directional elongation operates only on the integration fields that receive input from the LVF (for languages read from left to right). In the LVF, this modification leads to increased interference from leftward flankers and decreased interference from rightward flankers for targets; therefore, the recognition of a word's initial letter benefits from a greater release from crowding.

One issue with introducing crowding to help account for visual word recognition is whether or not word length (number of letters in a word) should be considered a crowding parameter. The majority of investigations on crowding have focused on the interference from the flanker closest to the target. Letter recognition within a word, however, nearly always involves flanking letters that are not just adjacent but also non-adjacent to the target letter location. The surrounding letters can create a host of perceptual difficulties for letter visibility depending on word length and eye fixation location. The decline of performance with the increasing number of flanking letters in a string has been attributed to independent contributions to letter–in-string visibility from crowding (Chanceaux, Mathôt, & Grainger, 2014) and from deployment of spatial attention to the letters in the string(Strasburger, Harvey, & Rentschler, 1991). Chanceaux, Mathôt, and Grainger (2013) demonstrated that the crowding zone of the target letter in their letter strings encompassed one inward and two outward flankers, consistent with the inward-outward asymmetry defined by the spatial extent of the crowding zone. They argued that, crowding, as seen for adjacent flankers, resulting from the excessive feature integration of information presented in the crowding zone, can apply to nonadjacent flanking letters as well. This suggests that crowding increases with the number of flanking elements in the crowding zone. In this sense, the MRF hypothesis generalizes a standard crowding effect according to Bouma's law (Bouma, 1970) oon the critical spacing limit between two adjacent letters to the integration interference from the number of elements entering the crowding zone defined by Nandy and Tjan (2012). The number of letters (in the integration zone), thus, is an essential component to any account of crowding effects in visual word recognition.

Given the consistency of findings across several experimental conditions – including centrally presented strings, strings presented peripherally in the LVF or RVF, and unilateral and bilateral strings in the one or both visual fields - the MRF hypothesis seems to provide a promising framework for the visual word recognition asymmetry based on the letter-specific crowding asymmetry between the visual fields (Tydgat & Grainger, 2009; Grainger et al., 2010; Chanceaux & Grainger, 2012; Chanceaux et al., 2013, 2014; Chanceaux & Grainger, 2013). Whether or not crowding asymmetry, as predicted by the MRF hypothesis, likewise contributes to letter recognition variability around fixation, however, has not been systematically examined.

It is critical for understanding visual word recognition to know whether or not letters surrounding a given letter in a fixated word contribute differentially to crowding effects as a function of the visual field and/or the number of elements in the crowding zone. We can address this via our VP paradigm, which employs all possible viewing positions and recognition of each individual letter in a string, and thus may circumvent a potential bias from spatial attention modulation. Studies have shown that attention to the target location can reduce crowding (Yeshurun & Rashal, 2010) and the crowding effect is smaller with unilateral than bilateral presentation (Chanceaux & Grainger, 2013). Finally, this is also an empirical way to evaluate the MLIP model.

4.2.1 The present study

The present study explores the extent to which crowding effects contribute to recognition asymmetries in the viewing position paradigm. Specifically, we adopt the MLIP framework for letter recognition in the two visual fields, in order to examine the contributions of visual acuity (as the MLIP model proposes) and visual crowding (as the MRF hypothesis suggests) to the recognition asymmetry observed in the VP curve.

To these ends, we reanalyzed the behavioral data from Experiments 1-3 (Chapters 2 and 3), with a focus on recognition performance (accuracy and reaction times) at various target character positions relative to fixation, visual field, and the number of elements appearing in the same visual field as the target. In addition, we used the data from the within-subjects design in Experiment 4 to determine whether our results were replicable, as well as to further explore whether the observed effects are stimulus-specific. At a general level, my goal was to identify factors that reliably contribute to the overall pattern of letter recognition in the viewing position paradigm. In so doing, I could evaluate the source(s) of the asymmetry in the VP curve. Specifically, I evaluated the impact of visual acuity and crowding in each visual field with regression analysis using a generalized linear mixed model. This allowed me to examine the assumptions of the MLIP model and the MRF hypothesis, and to propose an extension of the MLIP model of visual word recognition.

Datasets were for three different stimulus types: non-word letter strings, non-letter symbol strings, and non-linguistic ring sequences (Landolt C's horizontal arrays). Non-word letter strings were designed to isolate letter visibility from processing effects due to feedback from a word level representation. Behavioral performance for non-word letter strings would therefore align well with the present purpose of evaluating the asymmetry in letter visibility due to visual acuity and crowding. Additionally, in order to evaluate letter-specific crowding adaption in the LVF as proposed by the MRF hypothesis, the same analyses were conducted with recognition data from non-letter symbol strings and non-linguistic ring sequences (Chapter 3).

We hypothesized that both visual acuity and crowding contribute to the overall recognition pattern given that both place limits on the letter recognition function (Bouma, 1970). With respect to the visual field asymmetry, there should be larger visual acuity effect for target recognition in the LVF than in the RVF for letters and symbols but not for non-linguistics ring sequences, as suggested by the perceptual learning account and its instantiation in the MLIP model. Likewise, we expected a larger crowding effect in the LVF than RVF but only for letters and symbols; for non-linguistic ring sequences we expected an equivalent crowding effect in the two visual fields, as suggested by the MRF hypothesis. The VP effects for non-word letters, non-letter symbol strings, and non-linguistic ring sequences were reported in Chapter 2 and Chapter 3, and will not be discussed in the present chapter.

4.3 Experiment 1 - Experiment 3: Letter, Symbol, and Ring Character Recognition

4.4 Method

4.4.1 Data

The data used in the present study are from Experiments 1 to 3 of this dissertation. In these experiments, each stimulus (non-word letter string, non-letter symbol string, or non-linguistic ring sequence; see examples in 4.1) consists of five horizontally arranged characters with one of them serving as a target. Stimuli were presented for 20ms at various positions horizontally spanning fixation. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix. Strings were randomly divided into 25 conditions as a function of their presentation relative to fixation (fixation location) and target letter position within the string (target character position); each condition contains four types of items that vary with target characters. Participants performed a character discrimination task; letter discrimination for Experiment 1, symbol discrimination for Experiment 2, and character discrimination for Experiment 3. To examine factors varying with target presentation conditions (see Data Analysis section below for the details), we use the dataset that contains the human recognition performance with mean accuracy and mean reaction times by averaging over items (characters that used as targets) for each target presentation condition. There are 72 subjects with a total 504 observations per subject.

4.4.2 Data Analysis

Linear Mixed Regression. With the viewing position paradigm, the data of recognition performance consists of factors varying with target presentation conditions: each target's distance from fixation, the visual field in which each target was presented, the number of characters that were in the target's visual field. For our purpose of examining the contributions of visual acuity (as the MLIP model proposes) and visual crowding (as the MRF hypothesis suggests) to the recognition asymmetry observed in the VP curve, we use a linear mixed regression model to explore variables of target presentation conditions that can account for recognition performance in this viewing position paradigm. Linear regression has been used to examine the contributions of visual acuity or crowding effect in each of visual fields separately in the literature on the MLIP model (Nazir et al., 1991) and the MRF hypothesis (Chanceaux et al., 2014). As it has been shown that visual acuity and crowding are critical factors in visual perception (Chung et al., 2001; Intriligator & Cavanagh, 2001; Pelli et al., 2004) (or see D. Whitney and Levi (2011) for a review), and visual acuity asymmetry and visual field crowding asymmetry have been proposed to be crucial by the MLIP model and the MRF hypothesis, respectively, our linear mixed regression model consists of fixed effects that reflect these typical visual effects, including the distance-from-fixation effect (target's distance from fixation; visual acuity effect), the crowding effect (the interaction between target distance and the number of characters in target's visual field), visual field effect (the target's visual field; -1 was coded for targets in the LVF, 1 for the RVF, and 0 for the fixated target characters), visual acuity asymmetry (the interaction between target distance and visual field; visual acuity by visual field effect), and the crowding asymmetry (the interaction between crowding and visual field interaction; crowding by visual field effect); the random effects were intercept and slopes of subjects (Barr, Levy, Scheepers, & Tily, 2013). The linear mixed regression would thus determine the critical effects that explain the overall pattern of recognition performance manifest in the VP curve. Kenward-Roger approximation is used to determine the p-value.

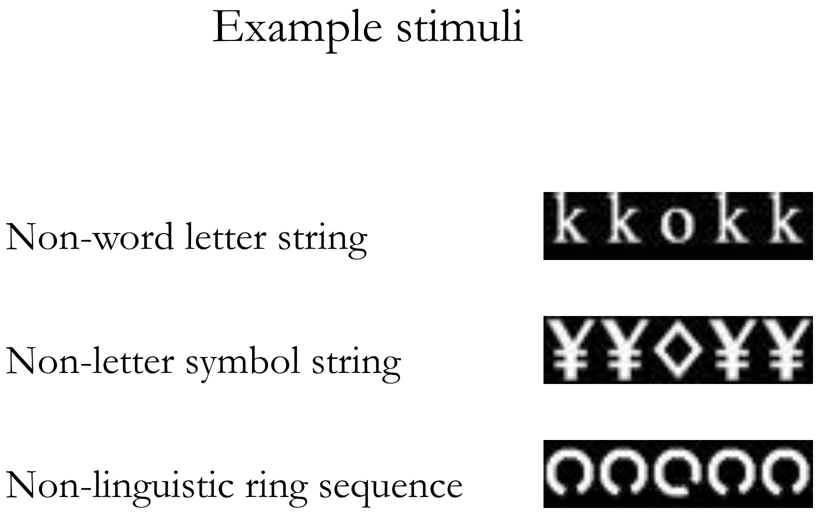

Figure 4.1: Example stimuli used in Experiment 1 - Experiment 3. Note: The target character (at center in these examples) could appear at any position in a string; each stimulus was presented spanning fixation at a random location relative to fixation.

4.5 Results

Regression analyses reveal similar recognition patterns for non-word letter strings and non-letter symbol strings which are distinguishable from those for non-linguistic ring sequences (See Table 4.1 for the details). In brief, non-linguistic ring sequences show no evidence of visual field asymmetry in any visual perceptual effects that we examined. By contrast, non-word letter strings and non-letter symbol strings show evidence of visual acuity asymmetry and crowding asymmetry, as detailed in the following.

Typical distance-from-fixation effects (visual acuity effects) are observed for non-word letter strings and non-letter symbol strings. Due to a large negative correlation of fixed effects between the distance-from-fixation and crowding variables ($r < -0.8$), the estimated distance-from-fixation effects show apparent recognition facilitation. This opposite direction of distance effect (visual acuity effect), however, reflects a collinearity in a current model but rather the nature of a relationship between the distance variable and the behavioral performance. In fact, our data show that the farther the letter and symbol target is away from fixation, the worse the recognition performance (lower mean recognition accuracy and higher mean reaction times) (See Figure 4.2) consistent with the literature. Although a residualizing procedure has been suggested to orthogonalize predicted variables (Baayen, 2008; Kuperman, Bertram, & Baayen, 2008; Jaeger, 2008), some criticism of whether residualized variables can be meaningfully interpreted have been raised (Wurm & Fisicaro, 2014). For our purpose of exploring variables that contribute to recognition performance in the viewing position paradigm and specifically of examining the crowding effect, we chose not to employ any residualizing procedure in the regression analysis. We also find significant crowding effects for all three types of stimuli: as the number of characters in the target's visual field increases, the distance-from-fixation effects have more and more deleterious impact on target recognition (See Figure 4.3).

Although the main effect of visual field is not significant for all three stimulus types, there is a significant visual field effect for non-wordlike letter strings with accuracy and for non-letter symbol stringswith the reaction times. Moreover, there is an asymmetric visual acuity effect between the two visual fields for letters and symbols – the drop-off of visual acuity is steeper in the LVF than in the RVF (See Figure 4.4), which has been previously reported and taken as a primary factor contributing to the visual field asymmetry in recognition Nazir et al. (1991). Note that due to a collinearity between the distance and crowding variables as discussed above, there is a negative coefficient of distance variable with the reaction times and a positive coefficient with accuracy as when the drop-off of visual acuity is steeper in the LVF than in the RVF.

Crowding asymmetry between the two visual field can better explain the variance of recognition performance (than visual acuity asymmetry). Our results show that crowding asymmetry significantly accounts for the recognition asymmetry of non-word letter strings and non-letter symbol strings. Non-linguistic ring sequences, on the other hand, do not show crowding asymmetry for either recognition accuracy or reaction times.

Further analyses on crowding asymmetry reveal a significantly larger crowding effect in the LVF than in the RVF for non-word letter strings (LVF - Accuracy: β= - 0.0176, $p < 0.0001$, RTs: β= 10.7535, $p < 0.0001$; RVF - Accuracy: β= - 0.0053, $p < 0.0001$, RTs: β= 6.1114, $p < 0.0001$) and non-letter symbol strings (LVF - Accuracy:

β= - 0.0081, $p<0.0001$, RTs: β= 7.1413, $p < 0.0001$; RVF - Accuracy: $p > 0.05$, RTs: β= 3.0085, $p < 0.01$). This larger crowding effect in the LVF may be the basis for the crowding asymmetry between two visual fields for both stimulus types. Non-linguistic ring sequences, by contrast, show similar crowding effects in the LVF and RVF. Figure 4.5 show separate regression coefficients of the crowding effect for LVF and RVF for non-word letter strings, non-letter symbol strings, and non-linguistic ring sequences.

Summary of Main Results

At a general level, my regression analyses indicate that the overall recognition data patterns are accounted for by the distance-from-fixation effect (visual acuity effect) and the crowding effect. The recognition asymmetry that characterizes non-word letter strings and non- letter symbol strings can be accounted for by visual acuity asymmetry and crowding asymmetry between the two visual fields: (1) the drop-off in visual acuity in the LVF is steeper than that in the RVF, (2) there is a larger crowding effect in the LVF than in the RVF. Non-linguistic ring sequences are characterized by significant but equivalent crowding effects in the two visual fields; there are overall symmetric visual acuity and crowding effects across target positions in the LVF and RVF.

Table 4.1: Results of Linear Mixed Regression with recognition accuracy and reaction times for Experiments 1-3. Regression coefficients are given. Note: R-squares that are reported in the Table 4.1 are conditional R-squares, which represent the proportion of variance explained by both the fixed and random factors (Nakagawa & Schielzeth, 2013; Johnson, 2014).

Random effects: subjects' intercept and slopes	Non-wordlike Letter strings		Non-letter Symbolic strings		Non-linguistic Ring sequences	
Fixed effects	ACC	RTs	ACC	RTs	ACC	RTs
Distance	**0.032** ***	**-25.24** ***	**0.010** **	**-10.510** ***	0.003	-1.171
Crowding	**-0.011** ***	**8.432** ***	**-0.006** **	**5.074** ***	**-0.008** **	**2.745** **
Visual Field	**0.017** **	-6.304 ^	0.002	**-6.894** *	-0.001	-1.566
Distance by visual fields	**-0.023** **	**8.321** *	-0.006	**9.023** *	-0.010	5.365
Crowding by visual fields	**0.006** **	**-2.321** *	**0.003** *	**-2.066** **	0.003	-1.427
R-square	0.732	0.920	0.851	0.941	0.706	0.912

^ $p < 0.06$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

ACC = accuracy as a dependent measure. RTs = reaction times as dependent measures.

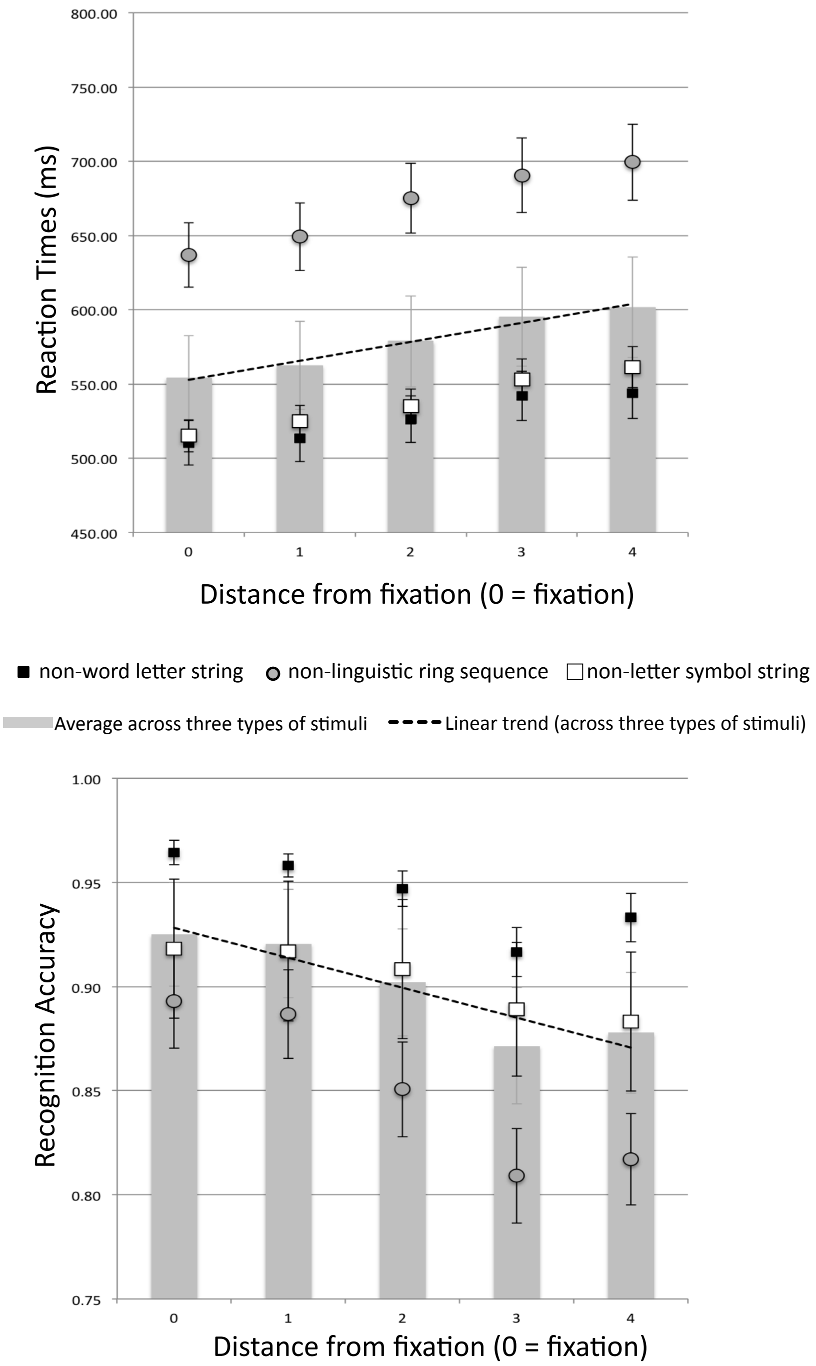

Figure 4.2: Recognition performance as a function of target distance from fixation (visual acuity) Experiments 1-3. Here we show the mean reaction times and accuracy for each condition. As the target moves away from fixation (visual acuity decreases), recognition accuracy decreases (top panel) and the reaction times increase (bottom panel).

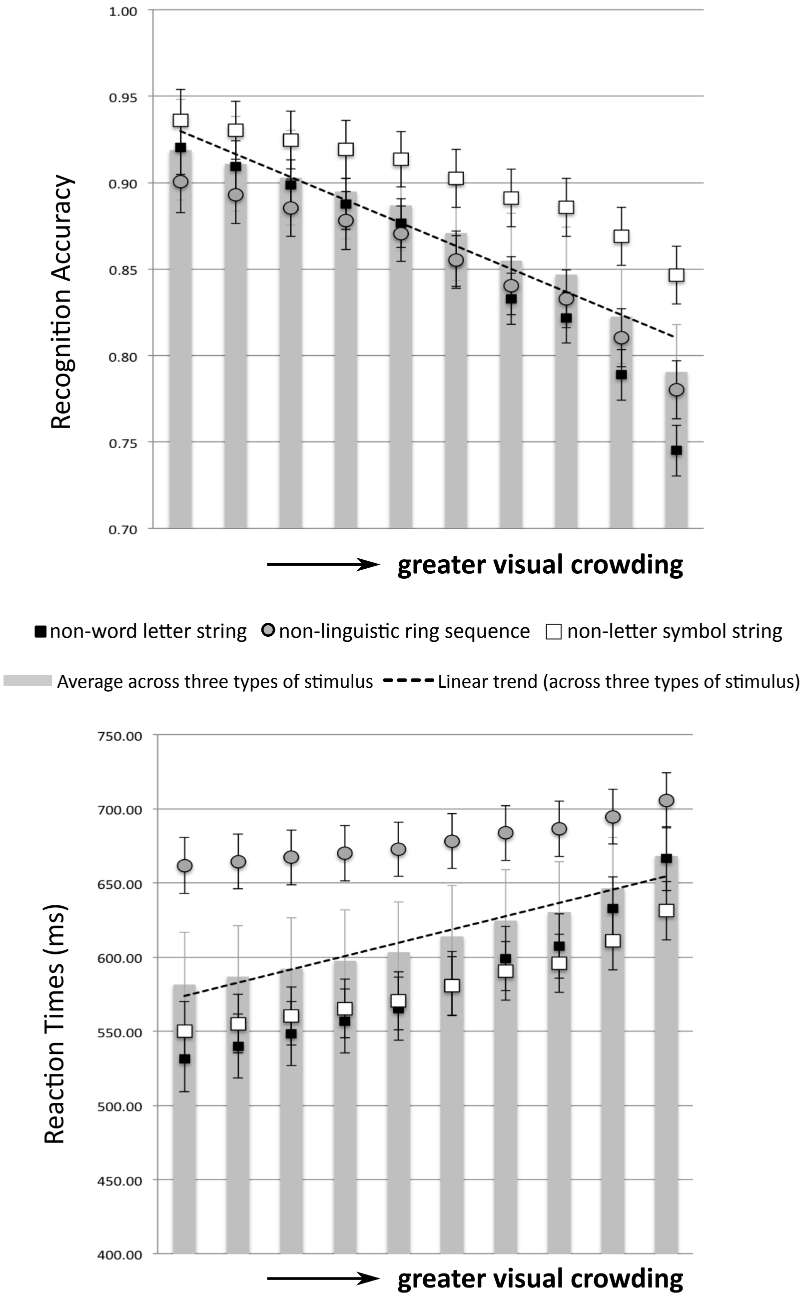

Figure 4.3: Recognition performance as a function of crowding. Experiments 1-3. Here we show the predicted reaction times and recognition accuracy for a given visual condition based on the linear mixed regression analyses. As the crowding effect increases, recognition accuracy decreases (top panel) and the reaction times increase (bottom panel).

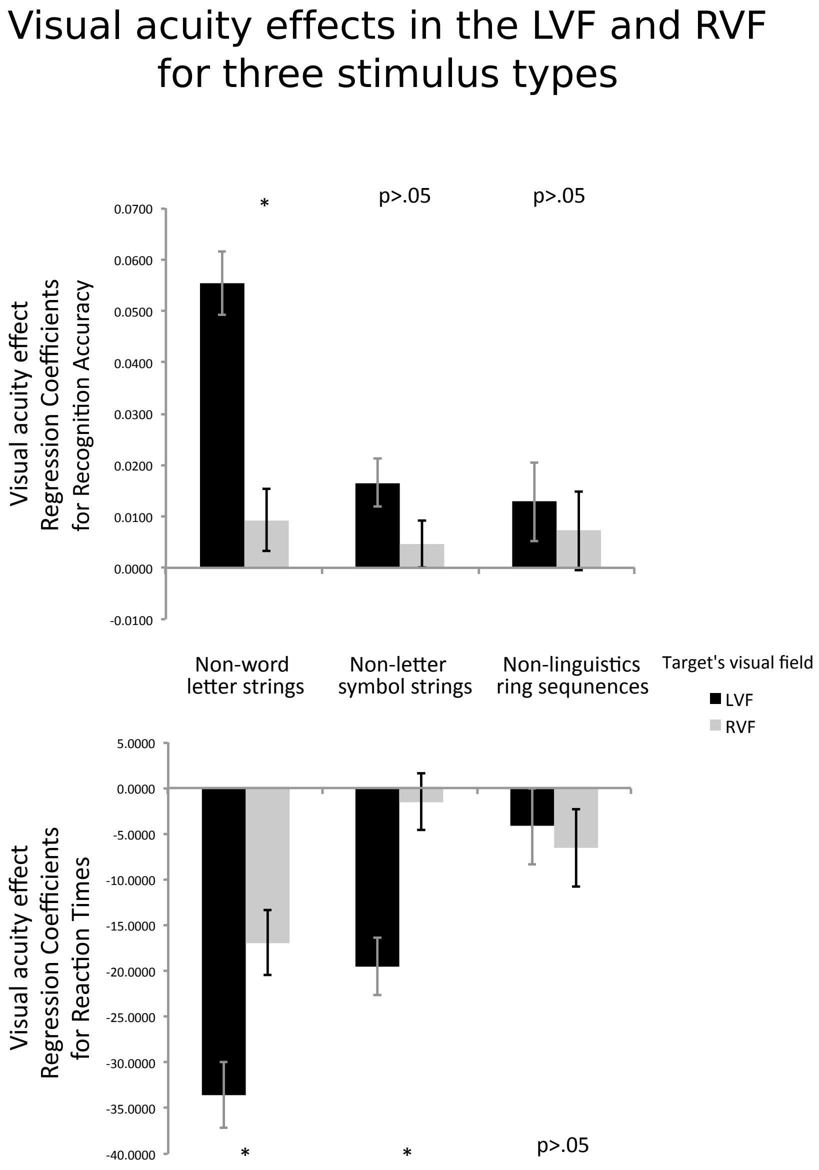

Figure 4.4: Regression coefficients of the visual acuity effect in the LVF and RVF in Experiments 1-3. For letters and symbols, there are larger distance effects (visual acuity effects) for target recognition in the LVF than RVF. By contrast, strings of non-linguistic ring sequences exhibit significant visual acuity effects in both visual fields, with no visual acuity asymmetry between the fields. Recognition accuracy is in the top panel and the reaction times are in the bottom panel. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

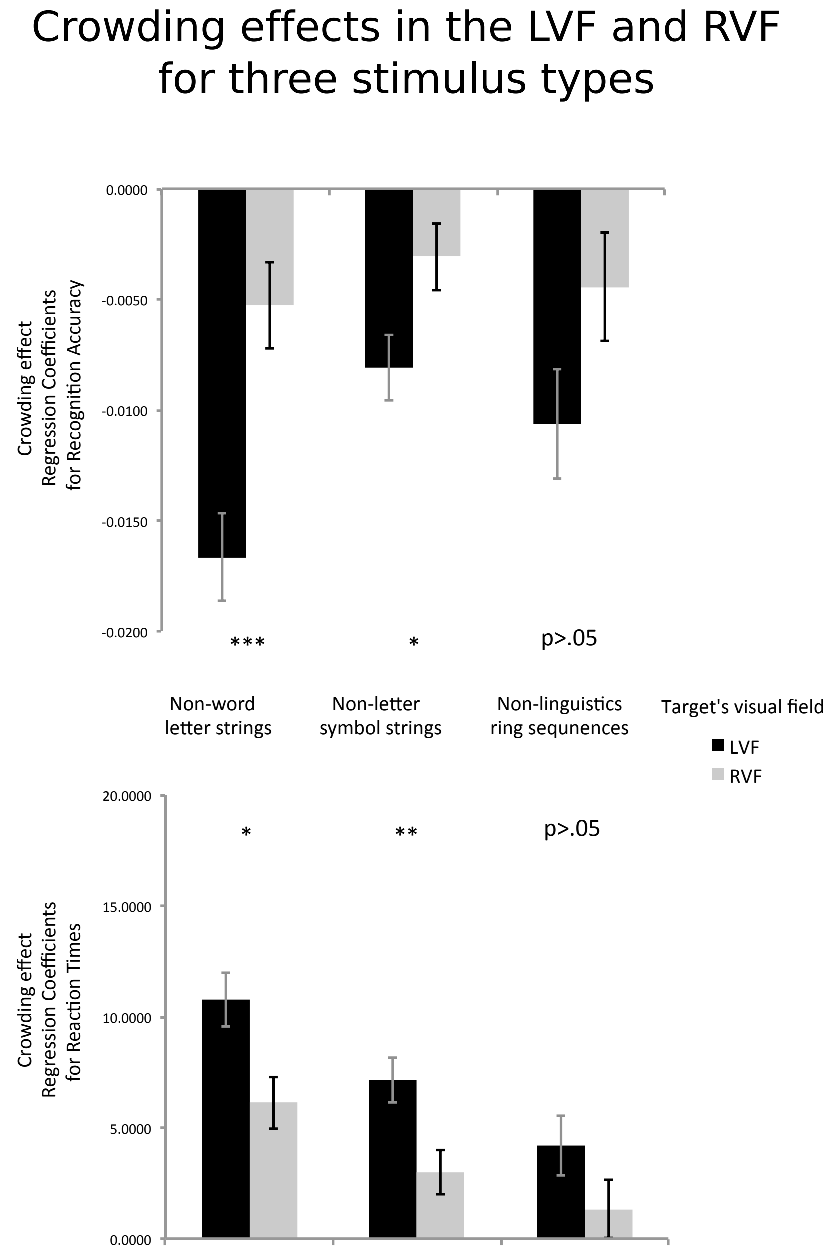

Figure 4.5: Regression coefficients of the crowding effect in the LVF and RVF in Experiments 1-3. For non-word letter strings and non-letter symbol strings, the crowding effect is larger in the LVF than RVF. This may lead to the crowding asymmetry between the two visual fields for letters and symbols. By contrast, there is no crowding asymmetry in target recognition for non-linguistic ring string sequences. These patterns are observed for both recognition accuracy (top panel) and reaction times (bottom panel). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.6 Experiment 4: Letter, Symbol, and Ring Character Recognition (Within-Subjects Design)

In Experiments 1, 2 and 3, we showed that the VP curve asymmetry observed for non-word letter strings and non-letter symbol strings could be accounted for by asymmetric visual acuity and crowding effects between the two visual fields, with a more pronounced asymmetric crowding effect than an asymmetric visual acuity effect. Non-linguistic ring sequences, by contrast, did not exhibit either a reliable visual acuity asymmetry or a reliable crowding asymmetry. These results suggest that human brains seem to treat strings of letters and symbols differently than ring sequences. In Experiment 4, we aimed to replicate these effects in a within-subjects design. Moreover, analyses of Experiments 1 – 3 data showed larger visual acuity and crowding effects in the LVF than in the RVF for both non-word letter strings and non-letter symbol strings. The findings that visual acuity and crowding asymmetry are crucial for non-word letter strings and non-letter symbols strings but not for non-linguistics ring sequences imply greater processing similarity between non-word letter strings and non- letter symbol strings than between either one of them and non- linguistic ring sequences. Conducting the same analyses within-subjects in Experiment 4 allows us to further examine whether non-word letter and non-letter symbol strings are treated more similarly than either of them and non-linguistic ring sequences. To this end, we use correlation analysis to evaluate the different relative contributions of different factors for these three stimulus types. We expected that the measures for non-linguistic ring sequences, at least the ones associated with visual acuity asymmetry effect and crowding asymmetry effect, would show a relatively low correlation with the measures for the other two stimulus types. By the same token, we expected measures for non-word letter strings and on non-letter symbol strings to be more highly correlated.

4.7 Method

4.7.1 Participants

Thirty-two students from the UCSD social sciences undergraduate subject pool participated in the experiment for either course credit or monetary compensation. Volunteers had a mean age of 20 (range: 18-25). Thirteen were male, eighteen female. All of them were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Eleven participants reported having a left-handed parent or sibling.

4.7.2 Stimuli and design

Non-word letter strings, non-letter symbol strings, and non-linguistic ring sequences served as stimuli. The parameters of stimulus size and designs were identical to those in Experiments 1 - 3.

4.7.3 Procedure

Each volunteer attended three experimental sessions within a week. Volunteers performed the target discrimination tasks for non-word letter strings, non-letter symbol strings, and non-linguistic ring sequences. The order of experiments was counterbalanced across volunteers. In all other aspects, the design was identical to that for Experiments 1 - 3.

4.7.4 Data Analysis

Linear Mixed Regression. Linear Mixed Regression. See Data analysis section in Experiments 1 - 3 for the details.

Correlation analysis. In addition to regression analyses, we do correlation analysis on regression coefficients for every pairwise combination of stimulus types. Therefore, for each regression coefficient – distance-from-fixation effect (visual acuity effect), visual acuity asymmetry effect, crowding effect, or crowding asymmetry effect – there are 3 correlational analyzes: (1) non-word letter strings versus non-letter symbol strings, (2) non-word letter strings versus non-linguistic ring sequences, and (3) non-letter symbol strings versus non-linguistic ring sequences. In so doing, we could evaluate the consistency of cross-experiment performance within the same individuals. Our regression analysis for Experiments 1 - 3 with the between-subjects design shows that significant factors contributing to character recognition in a non-linguistic ring sequences are different from the other two stimulus types, non-word letter strings and non-letter symbol strings. This seems suggest similarities in recognition performance for letters and symbols but dissimilarities between either with non-linguistic ring characters. If so, correlation analysis on regression coefficients would show relatively low correlations between non-linguistic ring sequences and either letters or symbols, compared to correlations on regression coefficients between letters and symbols. This correlation analysis will allows us to further evaluate the processing (dis)similarity among three types of stimulus.

4.8 Results

The within-subjects-analyses in Experiment 4 parallel those of the between-subjects-analyses in Experiments 1 - 3. For non-word letter strings and non-letter symbol strings, overall recognition patterns are accounted for by effects of distance-from-fixation (visual acuity), crowding, visual acuity asymmetry and crowding asymmetry. By contrast, crowding alone could account for the majority of the recognition data for non-linguistic ring sequences (See Table 4.2, for the details). Moreover, the crowding asymmetry observed for non-word letter strings and non-letter symbol strings is due to the more pronounced crowding effect in the LVF (Non-word letter string - Accuracy: $\beta = -0.0096$, $p < 0.0001$, RTs: $\beta = 10.3061$, $p < 0.0001$; Non-letter symbol string - Accuracy: $\beta = -0.0081$, $p < 0.001$, RTs: $\beta = 7.5286$, $p < 0.0001$) than RVF (Non-word letter string - Accuracy: $\beta = -0.0052$, $p < 0.0001$, RTs: $\beta = 4.5312$, $p < 0.001$; Non-letter symbol string - Accuracy: $p > 0.05$, RTs: $p > 0.05$). By contrast, there is no difference in crowding effects in the two visual fields for non-linguistic ring sequences (See Table 4.1 for the details. See also Figure 4.9).

We computed estimated regression coefficients of five predictors - distance-from- fixation (visual acuity), visual field, crowding, visual acuity asymmetry and crowding asymmetry variables - for each participant. With magnitude of regression coefficients as the dependent measurement, we conducted correlational analyses for every pair of stimulus types. There are significant correlations between non-word letter strings and non-letter symbol strings, for the distance-from-fixation effect (Accuracy: $r = 0.65$, $p < 0.0001$; RTs: $r = 0.35$, $p < 0.05$; See Figure 4.10), crowding effect (Accuracy: $r = 0.55$, $p < 0.001$; RTs: $r = 0.69$, $p < 0.0001$; See Figure 4.11), and distance by visual field asymmetry (Accuracy: $p > 0.1$; RTs: $r = 0.46$, $p <$

0.01; See Figure 4.13). Across all types of effects, distance-from-fixation (visual acuity) (Figure 4.10), visual field (Figure 4.11), crowding effect (Figure 4.12), visual acuity asymmetry effect (Figure 4.13) and crowding asymmetry effect (Figure 4.14), there are no significant correlations between non-linguistic ring sequences and either non-word letter strings or non-letter symbol strings.

Table 4.2: Results of Linear Mixed Regression with recognition accuracy and reaction times for Experiment 4. Regression coefficients-values are given. Note: R-squares that are reported in the Table 4.2 are conditional R-squares, which represent the proportion of variance explained by both the fixed and random factors (Nakagawa & Schielzeth, 2013; Johnson, 2014).

Random effects: subjects' intercept and slopes	Non-wordlike Letter strings		Non-letter Symbolic strings		Non-linguistic Ring sequences	
Fixed effects	ACC	RTs	ACC	RTs	ACC	RTs
Distance	**-0.018** ***	**-20.30** ***	**-0.011** *	-6.720 ^	-0.011	1.065
Crowding	**-0.007** ***	**7.419** ***	**-0.006** ***	**4.489** ***	**-0.009** ***	**1.875** **
Visual Field	-0.005	**-6.059** *	-0.002	**-9.037** **	0.010	-1.454
Distance by visual fields	-0.007	**10.842** **	-0.006	**11.611** **	-0.011	1.661
Crowding by visual fields	**0.002** *	**-2.887** ***	**0.003** *	**-3.040** **	0.002	-0.536
R-square	0.463	0.909	0.851	0.784	0.865	0.945

^ p < 0.06, * p < 0.05, ** p< 0.01, *** p<0.001

ACC = accuracy as a dependent measure. RTs = reaction times as dependent measures.

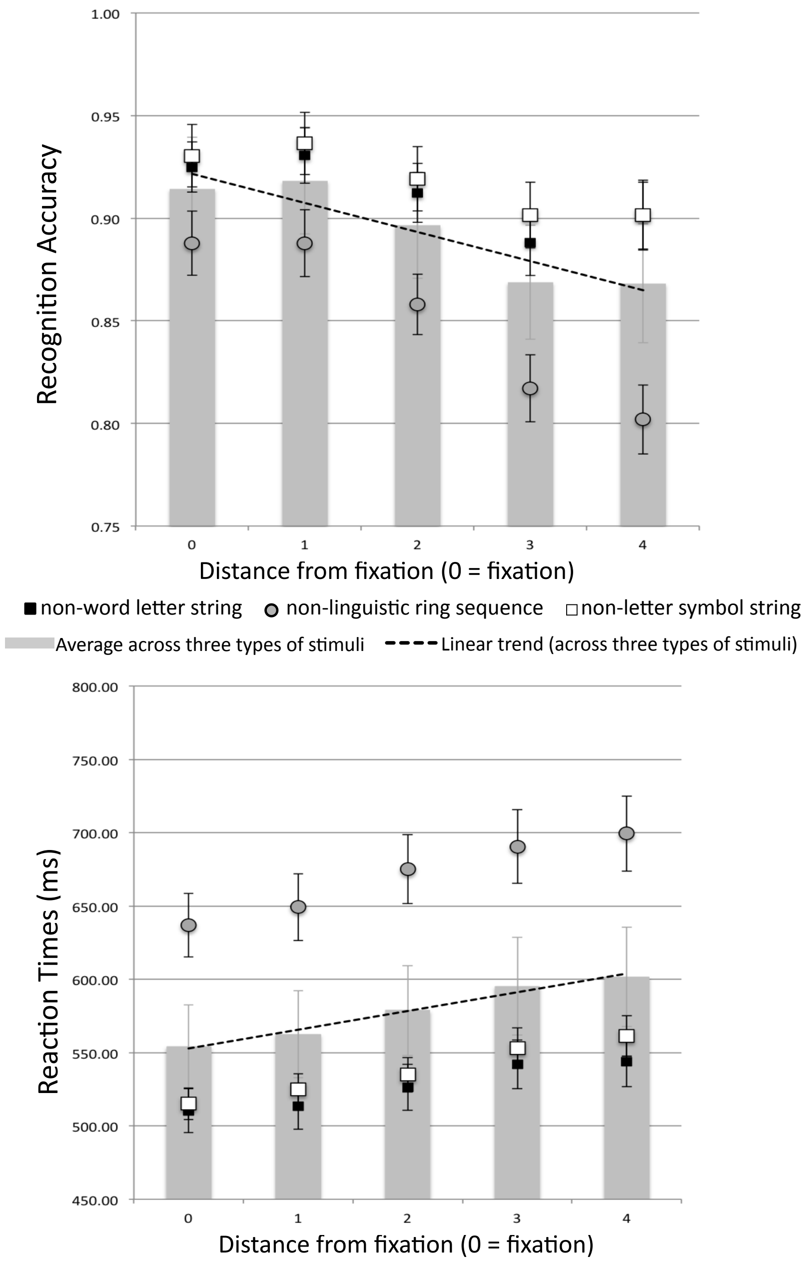

Figure 4.6: Recognition performance as a function of target distance from fixation (visual acuity) in Experiment 4. Here we show the mean reaction times and accuracy for each condition. As the target moves away from fixation (visual acuity decreases), recognition accuracy decreases (top panel) and the reaction times increase (bottom panel).

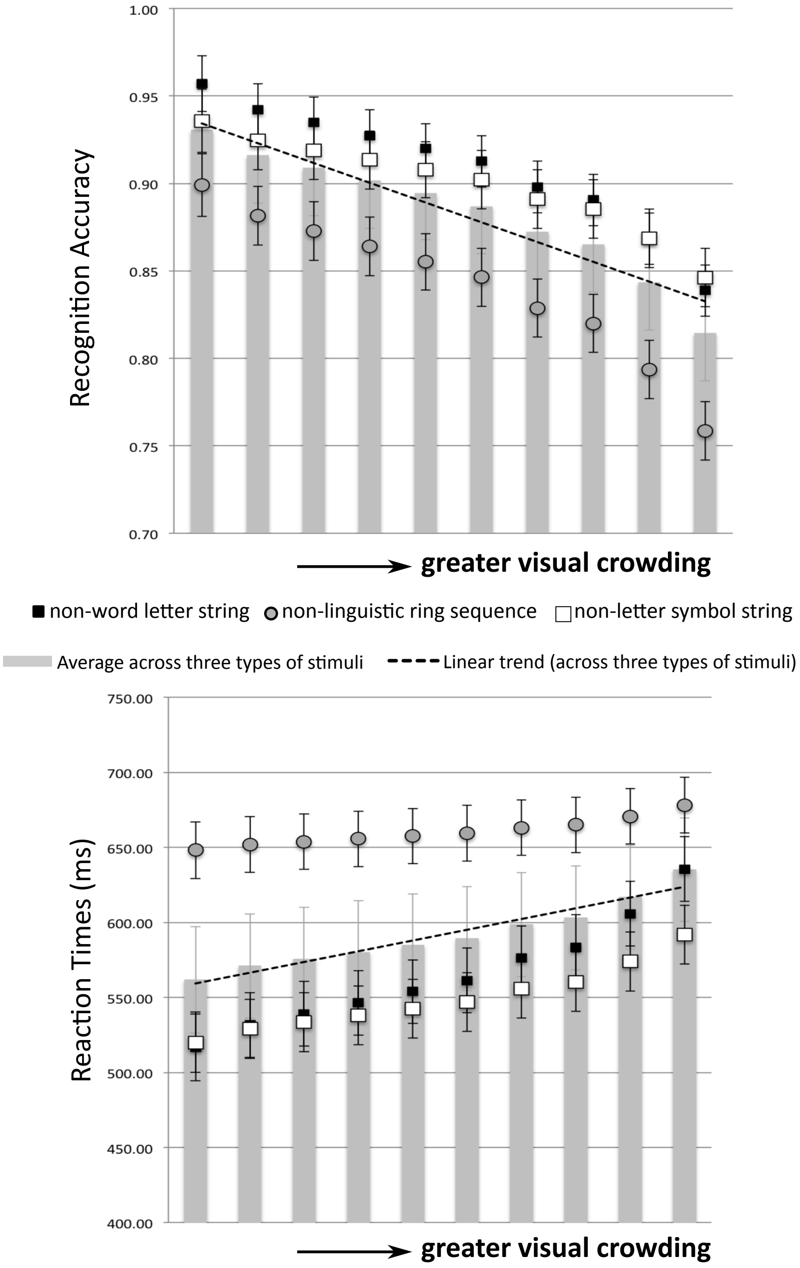

Figure 4.7: Recognition performance as a function of the crowding effect in Experiment 4. Here we show the predicted reaction times and accuracy for a given visual condition based on the linear mixed regression analyses. As the crowding effect increases, recognition accuracy decreases (top panel) and the reaction times increase (bottom panel).

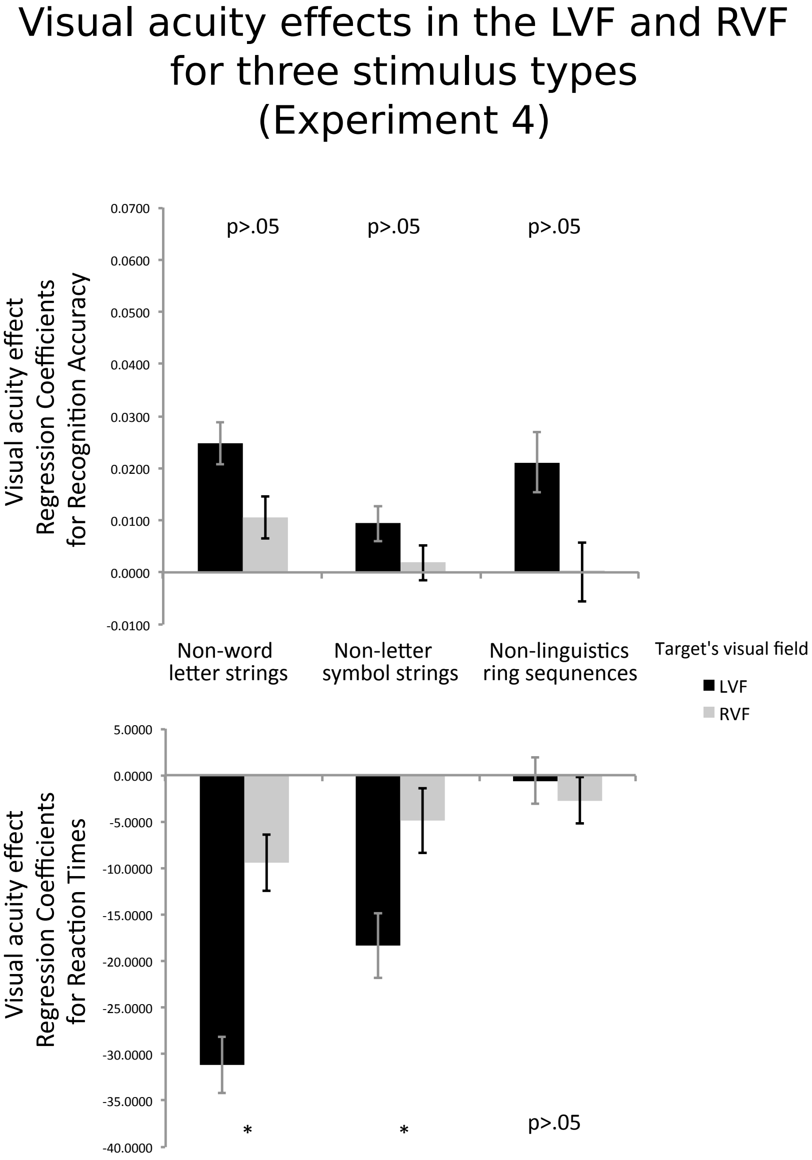

Figure 4.8: Regression coefficients of the visual acuity effect in the LVF and RVF in Experiment 4. For recognition accuracy (top panel), there is no reliable visual acuity asymmetry between the two visual fields for any of the stimulus types. For reaction times (bottom panel), there are visual acuity asymmetries for non-word letter strings and non-letter symbol strings. By contrast, non-linguistic ring sequences show no hint of visual acuity asymmetry between the two visual fields for either recognition accuracy or reaction times. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

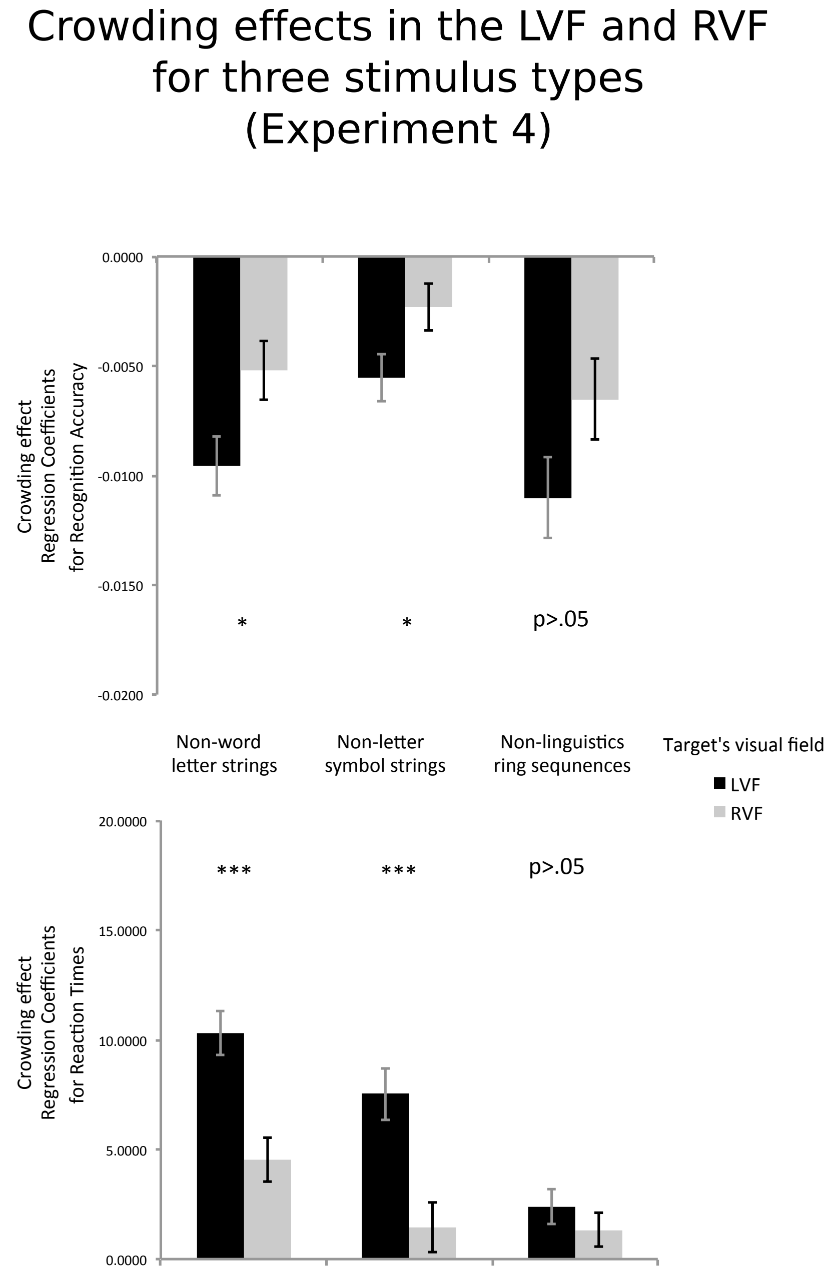

Figure 4.9: Regression coefficients of the crowding effect in the LVF and RVF in Experiments 4. For non-word letter strings and non-letter symbol strings, the crowding effect is larger in the LVF than RVF. This may lead to the crowding asymmetry between the two visual fields for letters and symbols. By contrast, there is no crowding asymmetry in target recognition for non-linguistic ring sequences. These patterns hold for both recognition accuracy (top panel) and reaction times (bottom panel). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

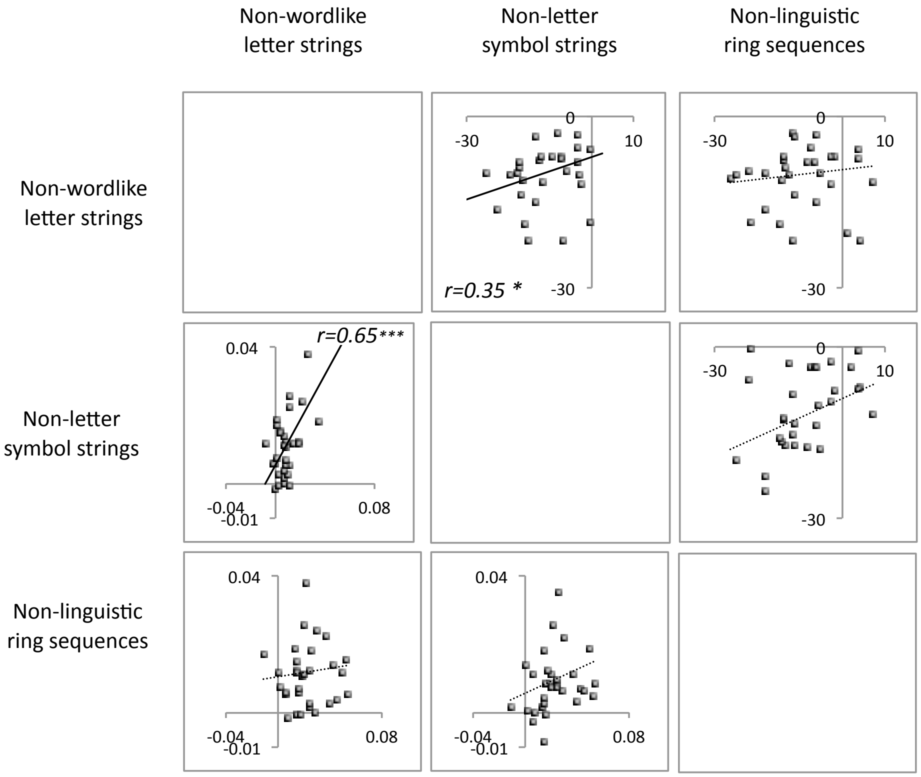

Figure 4.10: Correlation analyses of the distance-from-fixation effect (visual acuity effect) between the stimulus types. Coefficients of distance-from-fixation (visual acuity) effect for non-word letter strings are significantly correlated with those for non-letter symbol strings. There are no significant correlations on regression coefficients of visual acuity between those for non-linguistic ring sequences and non-word letter strings, nor between those for non-linguistic ring sequences and non-letter symbol strings. Plots at upper corner represent correlation analyses on reaction times and lower left on recognition accuracy. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

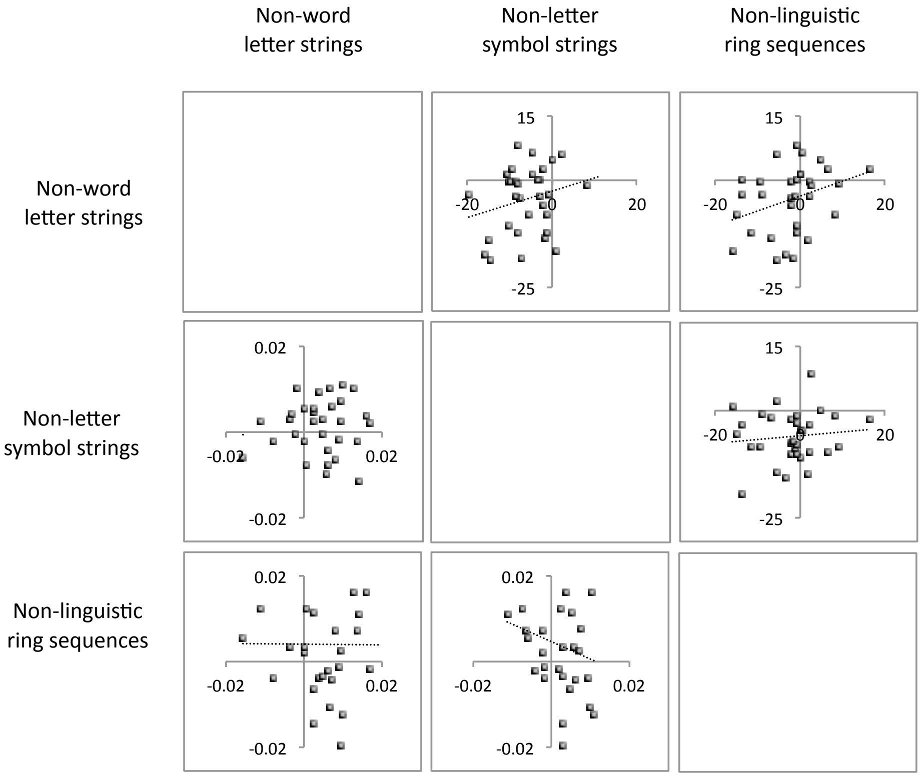

Figure 4.11: Correlation analyses of the visual field effect between the different the stimulus types. There are no significant correlations of regression coefficients of visual field found for any two stimulus types. Plots in upper corner represent correlation analyses for the reaction times and lower left are for recognition accuracy.

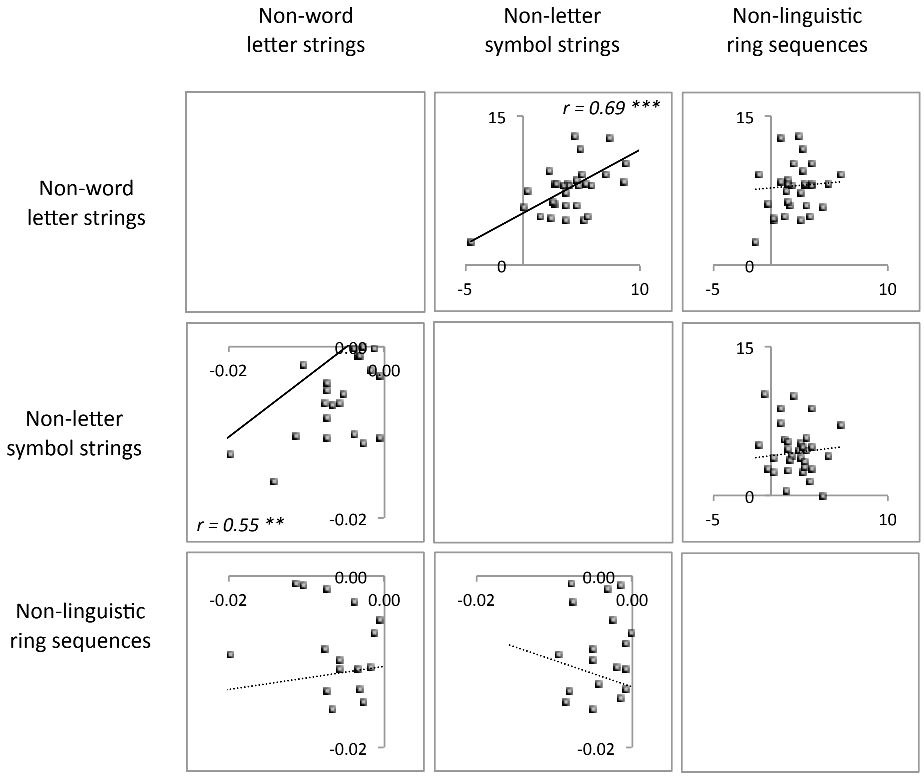

Figure 4.12: Correlation analyses of the crowding effect between the different the stimulus types. Coefficients of crowding effect for non-word letter strings are significantly correlated with those for non-letter symbol strings. There are no significant correlations of regression coefficients of crowding between those for non-linguistic ring sequences and non-word letter strings, nor between those for non-linguistic ring sequences and non-letter symbol strings. Plots at upper corner represent correlation analyses based on reaction times and lower left are based on recognition accuracy. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

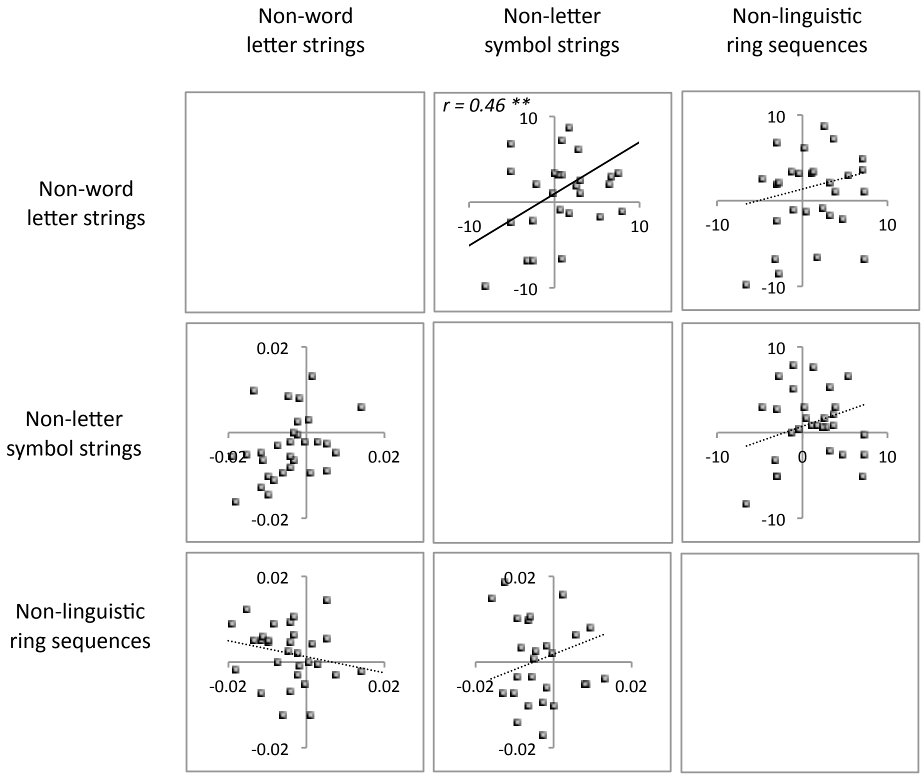

Figure 4.13: Correlation analyses on the distance-form-fixation by visual field asymmetry effect (visual acuity asymmetry effect) between the stimulus types. There are no significant correlations on regression coefficients of visual acuity asymmetry found between any of two stimulus types. Note that plots at upper corner represent correlation analyses based on the reaction times and lower left are based on recognition accuracy. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

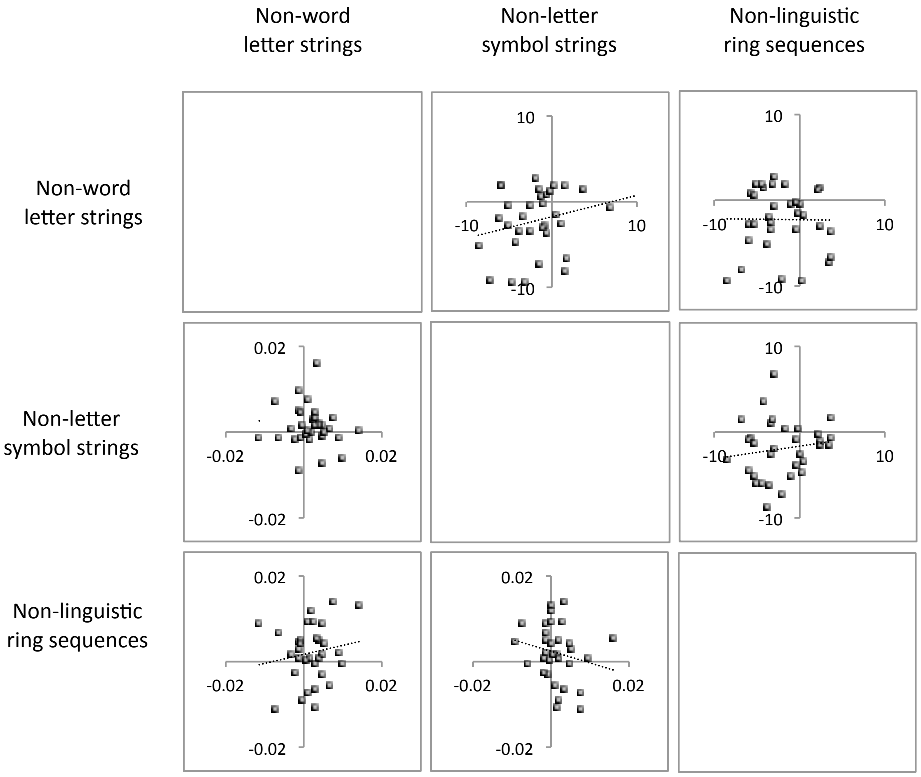

Figure 4.14: Correlation analyses of the crowding asymmetry effect between the stimulus types. There are no significant correlations between any two stimulus types. Plots at upper corner represent correlation analyses based on reaction times and lower left are based on recognition accuracy.

4.9 Discussion

Our results indicate that visual acuity and visual crowding both contribute to the overall VP curve. Studies have shown that both crowding and visual acuity play significant roles in visual recognition in visual space (Bouma, 1970), and hemispheric crowding asymmetry (Legge et al., 2001; Tydgat & Grainger, 2009; Grainger et al., 2010; Chanceaux & Grainger, 2012). We replicate these findings for our stimulus materials. Regression analyses for non-word letter strings and non-letter symbol strings reveal that crowding and crowding asymmetry combine with effects of distance-from-fixation (visual acuity) and visual acuity asymmetry to explain recognition patterns in the viewing position paradigm. Our results align with a recognition asymmetry between the visual fields, variously referred to as an asymmetry in perceptual span (McConkie & Rayner, 1975, 1976) [1], visual span (Legge et al., 2001), or the span of effective vision (Jacobs, 1986). Our finding of recognition asymmetry as a function of crowding is in line with demonstrations that isolated letter recognition is the same in the LVF and RVF (Bouma & Legein, 1977) but a RVF advantage emerges when these same letters are embedded in a string – i.e., when they are crowded (Bouma, 1973; Bouma & Legein, 1977). We extend these findings by showing that the letter recognition asymmetry is associated with different crowding effects in the two visual fields. Moreover, we find that consistent with the MRF hypothesis, the LVF shows a significantly larger recognition impairment due to crowding than the RVF. Although

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[1] At a general level, the literature uses these terminologies in a mixed way. However, it is noted that the authors who termed "visual span" had a specific claim to define the differences between perceptual span and visual span. Legge et al. (2001): "The notion of 'visual span' differs from the concept of 'perceptual span (McConkie & Rayner, 1975). The size of the 'perceptual span' depends on factors in addition to letter recognition. Operationally, it refers to the region of visual field that influences eye movements and fixation times in reading. McConkie and Rayner (1976) estimated that the perceptual span extends 15 characters to the right of fixation and four characters to the left."

the visual acuity asymmetry between the two visual fields could account for some of the variance in recognition in the VP curve, our results show that hemispheric crowding asymmetry also contributes; this is contra the proposal that the recognition asymmetry comes solely from a steeper drop-off in visual acuity in the LVF, as assumed by MLIP model.

We find no recognition asymmetry between the two visual fields for non- linguistic ring sequences - neither for visual acuity nor for visual crowding. In addition, regression analyses indicate that recognition for non-linguistic ring sequences is explained mostly by visual acuity and visual crowding compared to other factors proposed as important to recognition for letters. Our overall pattern of results holds whether the comparisons across stimulus strings are across or within-subjects. Not only do we replicate the asymmetries for letter and symbol strings and the absence of asymmetry for the ring sequences, but we show that effects found for letter strings are significantly positively correlated with those for symbol strings, while there is not even a hint of a correlation between effects found with ring strings and any other stimuli.

Taken together with our findings of crowding asymmetries for non-word letter strings and non-letter symbol strings, the null effect of crowding asymmetry for non- linguistic ring sequences is consistent with the MRF hypothesis regarding the stimulus-specificity of crowding effects. According to the MRF hypothesis, the spatial extent of the receptive field for letters is reduced compared to that for other kinds of visual objects, and receptive fields are leftward elongated for letters in the LVF (Tydgat & Grainger, 2009; Grainger et al., 2010; Chanceaux & Grainger, 2012). This special tuning for letters in skilled readers thus may lead to a reduced crowding effect compared to that for other kinds of visual objects, more so for information received in the LVF than RVF (Grainger et al., 2010). Although the neural mechanisms of crowding are not well understood (Pelli et al., 2004; Nandy & Tjan, 2012; Strasburger et al., 1991; Greenwood, Bex, & Dakin, 2009; Strasburger, 2005; Zhang, Zhang, Liu, & Yu, 2012; He, Cavanagh, & Intriligator, 1996), as per MRF, crowding reflects excessive feature integration or spatial pooling of target and adjacent characters in the integration zone (Wilkinson, Wilson, & Ellemberg, 1997; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Levi, Hariharan, & Klein, 2002; Pelli et al., 2004; Levi, 2008). On this view, our findings of crowding asymmetry for letters and symbols but not ring characters suggest that the spatial extent of the integration field might be modulated by stimulus type.

Such a stimulus-specific crowding effect, however, is contradictory to Pelli and Tillman (2008) who report that crowding operates independently of object type. Research shows that crowding is modulated by the visual complexity. Data show that crowding is modulated by the visual complexity (Grainger et al., 2010; Bernard & Chung, 2011), target-flanker similarity (Kooi, Toet, Tripathy, & Levi, 1994; Gheri, Morgan, & Solomon, 2007; Kennedy & Whitaker, 2010), dynamics between crowding and masking(Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009), attention (Yeshurun & Rashal, 2010; Chakravarthi & Cavanagh, 2009) and perceptual learning (Chung, 2007; Sun, Chung, & Tjan, 2010). The debate on whether or not crowding is independent of object types is in fact a debate on how to properly compare crowding effects across different visual stimuli. The extant data are based on different operational definitions across the studies. Pelli and Tillman (2008), for example, argue that stimulus properties might modulate the strength of crowding but not its spatial extent. That is, the contrast threshold (the ratio of flanked threshold over un-flanked threshold) as a function of spatial extent (of the integration field) could vary with the stimulus type in terms of the slope (the amplitude of crowding) of the function but not the locus of the inflection point (the value of spatial extent of crowding). According to Pelli and Tillman (2008), most studies do not disentangle the amplitude and spatial extent of crowding. In contrast to this threshold measurement, stimulus-specific crowding is inferred from the raw recognition accuracy data that have a small dynamic range between the floor at chance and the ceiling at one. This argument on the distinction between amplitude and spatial extent of crowding, indeed, indicates that the debate on crowding is not only about whether crowding is stimulus independent but also how divergent the definitions of crowding that researchers in the field adopt operationally and conceptually are.

Pelli and colleagues (Rosen, Chakravarthi, & Pelli, 2014) revise the notion of stimulus-independent crowding by limiting it to simple ”one-part” objects: crowding is equal across parts but not objects. They based their conclusion on their finding that crowding could be modulated by the location of features within an object, which consists of multiple parts. This view of stimulus-independent crowding suggests that crowding between parts, which is defined by the interference of feature combinations in the integration field, is stimulus-independent; crowding between objects, on the other hand, is stimulus-dependent. In other words, whether crowding is stimulus-independent or stimulus-specific depends on whether the visual stimulus is regarded as a part of or an object. What are parts and what are objects, however? Feature detection and feature combination are two primary components of object recognition (Treisman & Gelade, 1980), and crowding is considered a consequence of interference due to excessive feature combinations in the integration zone (Pelli et al., 2004). In this sense, the qualitative cognitive difference between a part and an object seems blurred. One can argue that stimulus-independent crowding applies to all kinds of "one-part" objects while another can argue for stimulus-dependent crowding since crowding depends on complexity (Bernard & Chung, 2011) as visual objects with "multiple-part" are more complex objects than "one-part" objects.

Our results for stimulus-specific crowding rest on the crowding asymmetry between the two visual fields for letters and symbols. Why is there a larger crowding effect in the LVF than RVF for letters and symbols? According to the MRF hypothesis, larger crowding in the LVF emerges from a leftward-elongated integration field in the LVF which optimizes processes for a word-beginning bias. Chanceaux and Grainger (2012) routinely find a larger initial letter benefit for strings presented in the LVF than RVF. They have argued that this larger initial letter benefit effect reflects the crowding asymmetry mechanism because other language-specific mechanisms, for example, a most informative initial letter, would predict the opposite pattern of a larger initial letter benefit in the RVF than LVF. In the present study, when we compare the recognition difference for the first and the second letter/symbol of a string presented in the LVF and RVF, we observe a larger difference (a benefit for the first than second character) for a string in the LVF. This difference, however, does not require us to assume a visual field difference because the first character of a string in the LVF is farther from fixation than the one of a string in the RVF and crowding is known to increase with the eccentricity. If crowding asymmetry is the mechanism that optimizes processing of the initial letter, as the MRF hypothesis proposes, then there should be an initial letter benefit from a target position function, which is averaged by collapsing over all string locations that were presented randomly spanning fixation. However, this is not what we find: we do not find the initial character benefit regardless of stimulus type, even though we do find significantly larger crowding in the LVF than RVF for letters and symbols. Our data cannot speak to the proposal that letter processing involves a leftward-elongated integration zone specific to the LVF. Given that the shape of the crowding zone has been suggested to be an eclipse along the temporal direction in both visual fields (Toet & Levi, 1992; Bouma, 1978), the crucial difference that leads to a crowding asymmetry might not be the shape but the size of the integration zones.

We speculate that the crowding asymmetry could be due, in part, to a modulation of the integration field in the LVF, for example, a change in size (i.e., there may be larger integration zones in the LVF compared to the RVF). Crowding effects in our regression analysis indicate that as the number of surrounding characters increases, there are greater recognition impairments with target distance from fixation. The crowding asymmetry implies that this change rate (slope) is larger in the LVF than RVF. Indeed, this is consistent with the general framework of Bouma's law (Bouma, 1970): crowding depends on the eccentricity of target; specifically, the spatial extent of crowding (usually referred as a critical spacing) is proportional to eccentricity. Moreover, given his finding of a larger number-of-letter effect in the LVF, Bouma (1973) suggested that "the spatial extent of foveally oriented masking is smaller in the R field than the Left" (p. 775). Therefore, the larger slope (larger change proportional to eccentricity) in the LVF seems to reflect larger spatial extent of integration zones in the LVF than RVF.

What might be the underlying mechanism for crowding asymmetry between the two visual fields? The MRF hypothesis proposes a special tuning of the crowding zone that is specific to stimuli that typically appear in strings and may be associated with location-specific letter detectors involved in parallel letter recognition (Grainger & Van Heuven, 2003). Our finding of crowding asymmetry for symbols as well suggests that this may be a mechanism that is specialized for familiar visual objects typically appearing in strings; it may not be specific to parallel letter recognition. Moreover, the SERIOL2 model (C. Whitney & Marton, 2013) proposes a (right) hemisphere-specific left-to-right inhibition (for languages read from left to right). Although SERIOL2 consistently predicts more pronounced crowding in the LVF compared to RVF, it specifies that this directional inhibition is only for letters and possibly numbers; it does not explain crowding asymmetry for symbols. On the other hand, a relationship between reading and crowding has been suggested. For example, reading rate is proportional to the size of the uncrowded span (Pelli et al., 2007) and there is a relatively smaller uncrowded span for dyslexic children compared to age-matched controls (Pelli & Tillman, 2008). Given that a developmental dyslexic's letter recognition is more severely impaired by surrounding flankers, it has been suggested that the spatial extent of the crowding zone might be larger in developmental dyslexia due to a lag in perceptual functioning (Bouma & Legein, 1977). In fact, studies have indicated that perceptual learning reduces crowding and the reduced crowding is specific to the trained stimuli(Wolford, Marchak, & Hughes, 1988; Huckauf & Nazir, 2007; Chung, 2007).

The stimulus-specific crowding effect, which we find with letters and symbols, may underlie the perceptual learning mechanism due to the intensive perceptual learning that occurs during reading. Symbols consist of the visual configurations that are shared with the human written system (Changizi, Zhang, Ye, & Shimojo, 2006), and thus may be perceptually trained during reading and treated by human visual system similarly to letters. Consequently, reading-related perceptual learning may lead to crowding asymmetry for letters and symbols and by the same logic not for ring characters.

4.10 Acknowledgement

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Chapter 5

Being a word, being asymmetrically optimal: word-specific asymmetric optimal viewing position (OVP) effect

5.1 Abstract

The present study aims to replicate the optimal viewing position (OVP) effect for words in a letter discrimination task within a viewing position paradigm. As expected, we find an asymmetric OVP effect for words but not for pseudowords having matching lexical properties. Moreover, words demonstrate an initial letter position advantage, which pseudowords do not possess. The distinctive VP effect for words suggests that mechanisms related or specific to word processing may contribute to the VP curve for words. Consistent with this speculation, our analysis shows that there is no perceptual asymmetry in letter recognition for words, although they do demonstrate the beginning vs end VP asymmetry. We have attributed the beginning vs end VP asymmetry for non-word letter strings and non-letter symbol strings to a visual field asymmetry in visual crowding, which could potentially be explained by the perceptual learning account of the asymmetric beginning-end VP effect for words.

We tentatively conclude that processes other than perceptual asymmetry contribute to the VP effect observed for words.

5.2 Introduction

Experiments 1 to Experiment 4 in this dissertation demonstrate asymmetric (beginning vs end) VP effects for non-word letter strings and non-letter symbol strings, but not for non-linguistic ring sequences. Moreover, the beginning vs end VP asymmetry is consistent with better performance in the RVF than in the LVF. This visual field asymmetry can be attributed to the steeper visual acuity drop-off in the LVF than in the RVF as well as to the larger crowding effect in the LVF than in the RVF. These results demonstrate that beginning-end asymmetric VP effects are not word-specific. The beginning vs end asymmetric VP effect with letters and letter-like strings is consistent with the suggestion that perceptual asymmetries may mediate the asymmetric VP effects.

Across these non-word stimuli, however, we do not find an asymmetric (left-of- center) OVP effect. Critically, however, an asymmetric OVP effect is one of the salient features of the VP curve in visual word recognition, and is reliably reported for words (Brysbaert & Nazir, 2005). Indeed, an asymmetric OVP effect for words has been reliably documented in a variety of tasks, including lexical decision (Brysbaert, 1992), naming (Brysbaert, 1994), and perceptual identification (Stevens & Grainger, 2003), in which the measure of performance at each fixation position derives from a single word recognition value. By contrast, the target discrimination task that we use in the series of studies in this dissertation offers a novel way to measure target recognition performance at any possible fixation position and letter position within a string. We adopted this task from our investigations of VP effect with non-word letter strings that usually are used to test a limited number of fixation locations (Nazir, O'Regan, & Jacobs, 1991; Nazir, Heller, & Sussmann, 1992; Nazir, 1993; Nazir, Jacobs, & O'Regan, 1998; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004), and extended it to test all possible fixation positions in order to depict the VP curve for non-word stimuli. To our knowledge, no prior studies have reported the VP curve using this letter discrimination task for words. It is, therefore, an empirical question whether there is an asymmetric (left-of-center) OVP effect for words in this target discrimination task. If words, unlike all other stimuli we have used, do demonstrate the asymmetric OVP in this task as well, it will suggest that the asymmetric OVP is word-specific. If however, the absence of the asymmetric OVP with letter and letter-like strings is due to the demands of our specific task, then words too may not demonstrate an asymmetric OVP effect in our letter discrimination task.

Depending on our results for words, it may or may not be an issue as to whether the two asymmetric VP effects - the asymmetric beginning vs end VP effect and the asymmetric OVP – emanate from the same mechanism. Given that non-word stimuli exhibit the beginning vs end asymmetric VP effect without the asymmetric OVP effect, if words both these effects, then there may be some dissociation between the responsible mechanisms. As noted in earlier chapters, the various theoretical accounts of the asymmetric VP effects do not differ for these two asymmetric VP effects. On the cerebral laterality account, the proposed mechanism for the beginning vs end VP effect focuses on the left-right hemispheric specialization for language processing; it is not intended to explain the asymmetric OVP (Brysbaert, 1994; Brysbaert, Vitu, & Schroyens, 1996). On the perceptual learning account, both VP curve asymmetries are taken to reflect the mediation of visual field asymmetry due to perceptual learning during reading (Nazir et al., 1991, 1992; Nazir, 1993; Nazir et al., 1998, 2004). Finally, although the relative distribution of informativeness within a word may account for the word only asymmetric OVP effect, it cannot account for the asymmetric beginning vs end asymmetric VP effect for non-word letter strings and non-letter symbol strings (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; O'Regan & Jacobs, 1992; Clark & O'Regan, 1999; Stevens & Grainger, 2003). Currently, we do not have a strong position on whether or not the two asymmetric VP effects rely on different mechanisms, but are of the opinion that empirical examinations of the VP effects across different stimulus types in the same task may provide a foundation for initiating a conversation. Here we investigate the VP curve for words and pseudowords.

We will examine the asymmetric (left-of-center) OVP effect for words and the beginning vs end asymmetry to determine whether visual field asymmetries mediate it. We will examine whether there is better letter recognition in the RVF than in the LVF, as well as a larger crowding effect in the LVF than in the RVF when the target letter is embedded in a word. According to the perceptual learning account, a visual field asymmetry mediates the asymmetric VP effects. Moreover, the crowding asymmetry between the two visual fields has been suggested to reflect perceptual adaptation for letters in the LVF that impairs recognition due to greater crowding in the LVF (Tydgat & Grainger, 2009; Grainger, Tydgat, & Isselé, 2010; Chanceaux & Grainger, 2012; Chanceaux, Mathôt, & Grainger, 2013). Although reading-experience-dependent mechanisms in letter recognition are usually examined in a context of letter strings, they should apply to words. Taken together, we anticipate a visual field asymmetry in recognition of target letters embedded in the word across the visual fields: (1) overall better performance for targets in the RVF than in the LVF, (2) greater drop-offs in visual acuity on target recognition in the LVF than in the RVF, (3) greater crowding effects on targets in the LVF than in the RVF. This pattern of effects would be consistent with a perceptual learning account. Deviations from this pattern would imply limits on a perceptual learning account of the beginning vs end VP asymmetry for words.

5.2.1 The present study

In Experiment 5, we examine the VP effects for words using the same letter discrimination task as we used with various non-word stimuli. Our primary aim is to replicate the widely-reported asymmetric OVP effect for words, observed with other tasks. Moreover, given that our task provides a richness of performance data – in letter recognition at each fixation position and letter position within a word – we will be able to examine potential visual field differences in letter recognition and the visual field crowding asymmetry. Tasks usually employed to investigate the VP effects, such as lexical decision or naming do not provide detailed enough data about letter recognition to assess the perceptual learning account; ours does.

Employing this letter discrimination task with words in the viewing position paradigm faces a number of difficulties given that word properties such as word frequency, as well as sublexical properties such as neighborhood frequency, and bigram frequency are known to contribute to visual word recognition, and thus must be controlled for. For Experiment 5, I thus generated a set of word stimuli for which several critical lexical properties over target positions and target letters were controlled. Furthermore, in anticipation of replicating the asymmetric OVP effect for words, in Experiment 6, we examined the VP curve for pseudowords. Pseudowords were created by replacing one letter from each word used in Experiment 5. This set of pseudowords also was controlled for the same word properties over target positions and target letters, as well as over target positions and the locus of replaced letter. At a general level, our aim was to determine the extent to which the asymmetric OVP effect is specific to words. Although pseudowords are not real words found in a dictionary, they are much more similar to words than non-word stimuli that we used in Experiment 1. For example, pseudowords are pronounceable; some are even pronounced like existing words; pseudowords consist of certain letter combinations that are found in real words rather than impossible letter strings of k (Experiment 1). Moreover, given the careful control of stimuli between Experiment 5 and Experiment 6, these pseudowords share similarities with words in many respects. If the asymmetric OVP is specific to words, there should be no asymmetric OVP effect for pseudowords. If however, the asymmetry of the OVP is not word specific but reflects the level of wordiness (via whatever sublexical processing), we may also see an asymmetric OVP for pseudowords.

5.3 Experiment 5: Letter Recognition in a Word

5.4 Method

5.4.1 Participants

Twenty-four students from the UCSD social sciences undergraduate subject pool participated in the experiment for either course credit or monetary compensation. Participants had a mean age of 21.83 (range: 19-27). Six were male; eighteen were female. All participants were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Nine participants reported having a left-handed parent or sibling.

5.4.2 Stimuli and design

The stimuli consisted of 400 five-letter words. Words were selected from WebCELEX database (Max Planck Institute for Psycholinguistics, 2001). The possible target letters were n, r, t, or l, and on a given trial one of these appeared at one of five letter positions within a word. Each word contained five distinct letters; each word contained only one target letter. Word frequency, orthographic neighborhood frequency, and bigram frequency were matched across target letters and across target letters at a given target letter position (See Table 5.1). Words were divided into 25 conditions as a function of their position relative to fixation (fixation location) and as a function of target letter position within the word (target letter position). For half the subjects, n and t served as target letters in separate sessions (one in each session); r and l served as distractors in both sessions. For the other half, r and l were targets and n and t were distractors. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix (A full list of the experimental stimuli is included in Appendix C).

5.4.3 Procedure

Participants performed a letter discrimination task (Figure 5.1A). A trial began with a fixation “+” flashed at the center of a computer screen for 500 msec. Once the fixation cross disappeared, a word was flashed for 20 msec. Figure 5.1B displays a trial sequence. Participants were asked to indicate whether or not a target letter was embedded in the word by pressing “Yes” or “No” response keys as quick and as accurate as possible. For half of the participants, the ”Yes” key were assigned to their right hand. For the other half, their left hand was assigned to the “No” key. The experiment contained two blocks. In each block, participants pressed a button to discriminate the target character from among two possible distractors. Overall, 300 trials per block were distributed across 5 runs of 60 (See Table 5.9, Appendix D).

5.4.4 Offline measures

Participants were administrated offline tests in a separate online-testing session within a week after attending the letter discrimination experiment. Tests included lexicon comprehension tests and familiarity rating. For the former participants were instructed to choose the correct meaning out of 5 options for each word in the experiment. For the latter, participants were asked to rate their familiarity with each word on a five-point scale (1-least familiar; 5-most familiar). On average, participants correctly answered 79% of the items in the lexicon comprehension test; across target letters and target positions, average scores range from 69% to 87%. One-way ANOVAs with the factor target position reveals no significant differences in comprehension scores across target letter positions (by-subject: $p > 0.05$, by-item: $p >$

0.05). The average familiarity ratings was 1.57 (out of 5; 5-most familiar), ranging from 1.33 to 1.96 across target letters and the target positions. One-way ANOVAs with the factor target position shows a significant difference in familiarity ratings across target positions by subject (F (4, 124) = 14.95, $p < 0.001$) while the difference is not significant by items ($p > 0.05$). See Table 5.2.

5.4.5 Data Analysis

Analyses used for words were identical to those for Experiments 1 in Chapter 2 and Chapter 4, including the two-way Analyses of variance (ANOVAs) with fixation position and target location, linear trend analyses with fixation position and target location, Point-to-Point Distance method for visual field asymmetry, and mixed linear regression. See the methodology in Chapter 2 and Chapter 4 for details. Given our findings with various non-word strings, our analysis for words will focus on (1) whether there is an asymmetric VP effect (beginning vs. end letters) via a linear trend test for fixation positions; (2) whether the OVP is asymmetric, i.e. shows optimal performance for a fixation at the second letter of a word; (3) whether performance is generally better in the RVF than in the LVF, which has been shown for non-word letter strings and non-letter symbol strings. Non-word letter strings and non-letter symbol strings also demonstrate an asymmetric VP (beginning vs. end) effect; (4) whether both visual acuity and crowding contribute to the overall recognition pattern in the viewing position paradigm; (5) finally, whether there is a visual acuity asymmetry and a crowding asymmetry between the two visual fields.

Table 5.1: Stimulus factors controlled for in Experiment 5, with means and standard error of the mean (SEM) information.

A. Word Frequency (per million)			Target Position		
Target Letter	1	2	3	4	5
l	111 (37)	117 (17)	110 (41)	115 (23)	113 (45)
n	125 (56)	128 (61)	111 (27)	107 (36)	113 (35)
r	124 (45)	123 (25)	111 (17)	103 (25)	113 (23)
t	110 (36)	125 (28)	109 (33)	112 (26)	108 (25)

B. Orthographic Neighborhood Size			Target Position		
Target Letter	1	2	3	4	5
l	4.45 (0.79)	2.90 (0.50)	3.60 (0.54)	2.95 (0.64)	2.25 (0.45)
n	3.55 (0.77)	1.45 (0.38)	4.80 (0.88)	3.80 (0.82)	2.75 (0.90)
r	4.75 (1.15)	3.50 (0.57)	2.15 (0.33)	2.70 (0.68)	2.55 (0.58)
t	4.00 (0.67)	4.30 (0.76)	4.30 (0.89)	3.15 (0.65)	2.55 (0.42)

C. Orthographic Neighborhood Frequency			Target Position		
Target Letter	1	2	3	4	5
l	6.60 (2.22)	6.94 (1.03)	6.54 (2.42)	6.85 (1.35)	6.73 (2.70)
n	7.80 (3.39)	7.65 (3.61)	6.89 (1.65)	7.08 (2.23)	6.71 (2.11)
r	7.36 (2.65)	7.38 (1.49)	6.61 (0.99)	6.18 (1.48)	7.03 (1.43)
t	6.56 (2.13)	7.46 (1.67)	6.79 (1.98)	6.65(1.53)	6.40 (1.50)

D. Number of Bigrams			Target Position		
Target Letter	1	2	3	4	5
l	2527 (216)	2631 (172)	2473 (180)	2411 (183)	2378 (146)
n	2786 (239)	2742 (314)	4025 (257)	3872 (350)	4062 (287)
r	3262 (223)	2974 (144)	2953 (259)	3264 (294)	3773 (224)
t	3102 (271)	4046 (148)	3662 (349)	3583 (307)	2879 (227)

E.Number of Bigram (based on every two letter positions in a word)				
Target Letter	1-2	2-3	3-4	4-5
l	628 (69)	716 (72)	576 (70)	564 (77)
n	716 (97)	875 (128)	937 (125)	969 (145)
r	722 (82)	859 (119)	726 (114)	939 (149)
t	970 (109)	784 (91)	854 (104)	846 (104)

Table 5.2: Offline tests for Experiment 5, with means and standard error of the mean (SEM) information.

Comprehension scores (accuracy)	Target Position				
Target Letter	1	2	3	4	5
l	0.73 (0.04)	0.80 (0.04)	0.71 (0.04)	0.79 (0.04)	0.73 (0.04)
n	0.79 (0.02)	0.87 (0.02)	0.84 (0.02)	0.83 (0.03)	0.80 (0.02)
r	0.74 (0.04)	0.73 (0.04)	0.86 (0.04)	0.80 (0.04)	0.83 (0.04)
t	0.85 (0.04)	0.73 (0.04)	0.76 (0.04)	0.69 (0.03)	0.83 (0.04)

Familiarity ratings	Target Position				
Target Letter	1	2	3	4	5
l	1.49 (0.10)	1.31 (0.11)	1.68 (0.09)	1.49 (0.11)	1.61 (0.10)
n	1.69 (0.10)	1.65 (0.10)	1.45 (0.10)	1.60 (0.09)	1.80 (0.10)
r	1.55 (0.11)	1.35 (0.11)	1.42 (0.10)	1.70 (0.12)	1.53 (0.10)
t	1.33 (0.09)	1.69 (0.11)	1.67 (0.09)	1.96 (0.11)	1.43 (0.09)

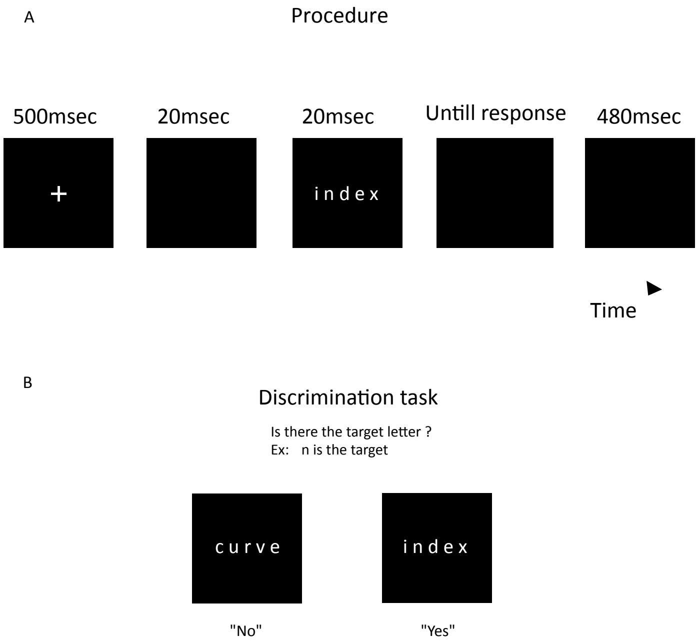


Figure 5.1: Procedure and task. A: procedure for a single trial in the viewing position paradigm. B: Example of letter discrimination task used in Experiment 1. Note that a target letter could be at any one of five letter position within a string.

5.5 Results

Analyses of variance (ANOVAs). There is a significant main effect of fixation position (Accuracy: F (4, 124) = 16.64, $p < 0.0001$; RTs: F (4, 124) = 37.17, $p < 0.0001$). Tukey post-hoc analyses indicate that recognition accuracy is significantly higher when fixation is at the second letter than the first ($p < 0.05$), and recognition accuracy is significantly lower at the last letter (See Figure 5.2). The main effect of target position is also significant (Accuracy: F (4, 124) = 5.82, $p < 0.0005$; RTs: F (4, 124) = 7.83, $p < 0.0001$). Tukey post-hoc analyses on target location, however, do not show significant accuracy differences between any pair of target positions (See Figure 5.3). There is a significant interaction between fixation position and target position (Accuracy: F (16, 496) = 2.45, $p < 0.005$; RTs: F (16, 496) = 2.28, $p < 0.005$). Multiple comparison tests show that when the target is in the first half of the word (1-2 out of 5), recognition performance is best (highest recognition accuracy and lowest reaction times) for fixations at the second and third letter positions, and performance is worst for a fixation at the word's last letter. When the target letter is in the latter half of the word (4-5 out of 5), recognition performance is worse for a fixation at the word's first letter compared to any other position. When the target is at the center (the 3rd letter position) of a word, there is trend for better performance for a fixation at the word center.

Linear and quadratic trend analyses with fixation position and target location. Recognition probability averaged over all possible target positions varies as a function of initial fixation position with a significant quadratic trend (Accuracy: t (127) = -8.05, $p < 0.0001$; RTs: t (127) = 11.96, $p < 0.0001$); however, the linear trend for fixation position is not significant (Accuracy: $p > 0.1$, RTs: $p > 0.1$) (See

Figure 5.2). Target position shows a significant linear trend for recognition accuracy (t (127) = -2.70, $p < 0.01$) but not RTs ($p > 0.10$), as well as a significant quadratic trend for accuracy (t (127) = -2.46, $p < 0.05$) but not for RTs ($p > 0.1$). See Figure 5.3. This is the first time we show the significant linear relationship between target positions and recognition performance in this series of dissertation experiments across a range of more or less word-like stimulus strings.

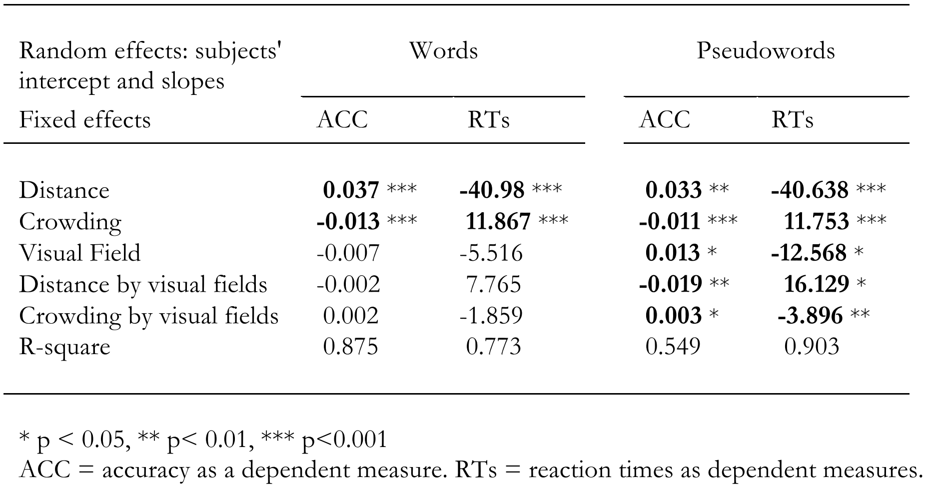
Similarity measure between the two visual fields: point-to-point distance. The similarity measure demonstrates no differences in recognition performance (accuracy and RTs) between the two visual fields. This is observed for analyses based on the whole dataset (Accuracy: $p > 0.1$; RTs: $p > 0.1$) as well as a subset with fixations at the first and last letters only (Accuracy: $p > 0.1$; RTs: $p > 0.1$). See Figure 5.4 and Figure 5.4.

Linear Mixed regression. Our results show that both visual acuity and visual crowding contribute to the recognition performance for the target letter discrimination for words in the viewing position paradigm. The contribution of visual acuity manifest as a typical distance-from-fixation effect: as a target moves farther from fixation, accuracy decreases and RTs increase. The contribution of visual crowding shows that the impact of this distance-from-fixation effect increases with the number of characters in the target's visual field (See Table 5.3). The distance by visual field and crowding asymmetry, however, is not a significant factor that accounts for recognition performance (See Figure 5.6), neither is the visual field crowding asymmetry (See Figure 5.7).

Summary of Main Results

The VP curve for words is asymmetric, with better performance at the beginning than at the end of a word and best performance at a left-to-center OVP. Moreover, there is linear relationship between performance and letter target position within the word: recognition is better for the target letters in the initial word positions. Recognition of LVF and RVF targets, however, did not differ. The overall target recognition pattern can be accounted by visual acuity and crowding. Both visual fields show similar effects of acuity and crowding, and we do not find visual field asymmetries for either.

Table 5.3: Linear Mixed Regression for Experiment 5 and Experiment 6. Regression coefficients are given. Note: R-squares that are reported in the Table 5.3 are conditional R-squares, which represent the proportion of variance explained by both the fixed and random factors (Nakagawa & Schielzeth, 2013; Johnson, 2014).



Random effects: subjects' intercept and slopes	Words		Pseudowords	
Fixed effects	ACC	RTs	ACC	RTs
Distance	**0.037** ***	**-40.98** ***	**0.033** **	**-40.638** ***
Crowding	**-0.013** ***	**11.867** ***	**-0.011** ***	**11.753** ***
Visual Field	-0.007	-5.516	**0.013** *	**-12.568** *
Distance by visual fields	-0.002	7.765	**-0.019** **	**16.129** *
Crowding by visual fields	0.002	-1.859	**0.003** *	**-3.896** **
R-square	0.875	0.773	0.549	0.903

* $p < 0.05$, ** $p< 0.01$, *** $p<0.001$

ACC = accuracy as a dependent measure. RTs = reaction times as dependent measures.

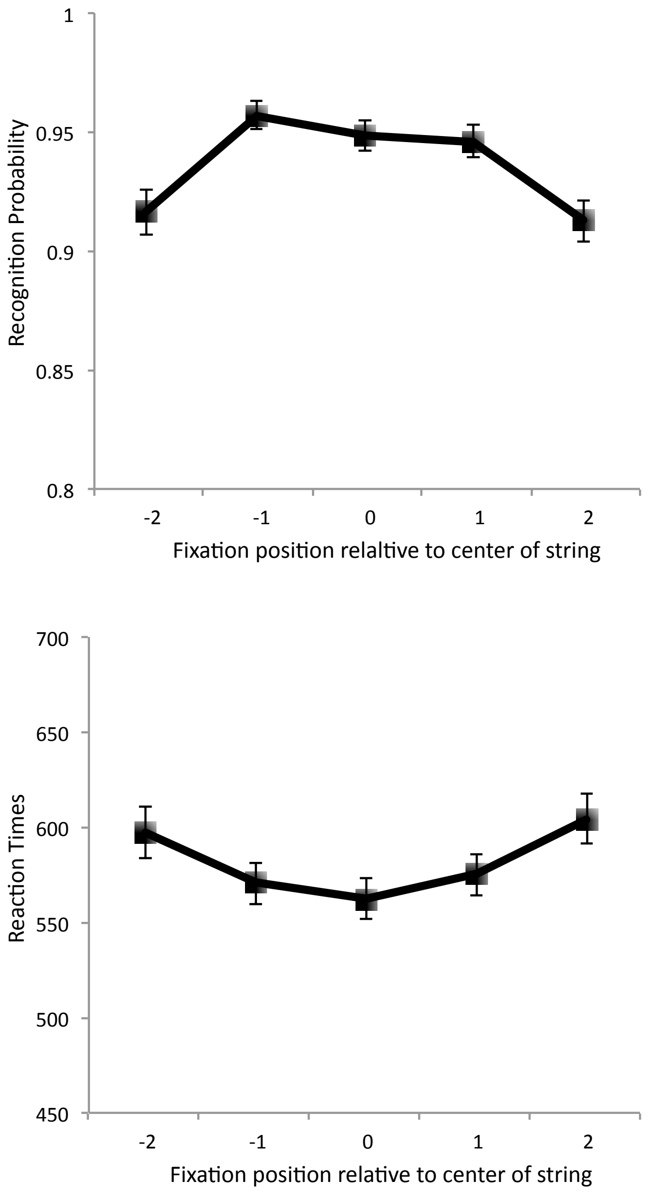


Figure 5.2: Two VP curves for accuracy and reaction times for words. Note the asymmetric beginning vs end viewing position effect for words: letter recognition is more accurate and faster when eyes initially fixate the beginning of a word. Moreover, the OVP is at the left-to-center of a word. Top panel, recognition accuracy of correct symbol recognition as a function of fixation position, collapsed across target positions. Bottom panel, recognition times of correct symbol recognition as a function of fixation position, collapsed across target positions.

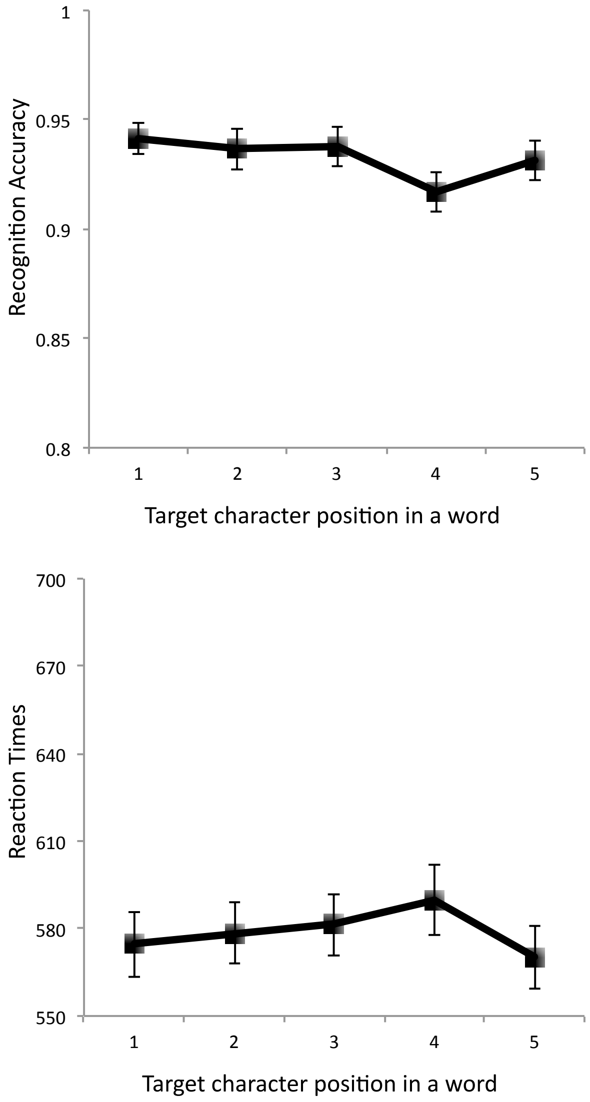


Figure 5.3: Target letter position function for words. Both recognition accuracy and the relative times show a significant quadratic trend. Recognition accuracy shows a significant linear trend for target position, suggesting the initial letter benefit for targets at the beginning of a word. Top panel, character recognition probability as a function of target letter position, collapsed across fixation positions. Bottom panel, reaction times for correct character recognition as a function of target letter position, collapsed across fixation positions.

5.6 Experiment 6: Letter Recognition in a Pseudoword

5.7 Method

5.7.1 Participants

Twenty students from the UCSD social sciences undergraduate subject pool participated in the experiment for either a course credit or monetary compensation. Participants had a mean age of 20.15 (range: 18-22). Five were male, and fifteen were female. All of them were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Ten volunteers reported having a left-handed parent or sibling.

5.7.2 Stimuli and design

The stimuli consisted of 400 five-letter pseudowords. Each (pronounceable) pseudoword was generated by replacing one letter of a word from Experiment 5 with another appropriate letter. The same target letters – n, r, t, l – served as target letters. On a given trial one of these was embedded in one of five letter positions within a word. Each pseudoword contains five distinct letters, of which one is a target letter. Orthographic neighborhood frequency and bigrams were matched across target letters, across target letters at a given target letter position, across letter position being changed, and across target letters at a given letter position being changed (See Table 5.4 and Table 5.5). Pseudo-words were divided into 25 conditions as a function of their presentation relative to fixation (fixation location) and as a function of target letter position within the pseudo-word (target letter position). For half the subjects, n and t served as target letters in separate sessions (one in each session); r and l served as distractors in both sessions. For the other half, r and l were targets and n and t were distractors. Each character subtended .3° of visual angle at a distance of 85 cm and was defined in a 44 x 36 pixel matrix (A full list of the experimental stimuli is included in Appendix D).

5.7.3 Procedure

The procedure used for this experiment was identical to that used in Experiment 5.

5.7.4 Offline measures

Participants were administrated offline tests in a separate online-testing session within a week after the experiment. Participants were not told that the items were not real words. Instead, they were instructed to rate the familiarity and the pronounceability of each "difficult word", with a five-point (1-less to 5-most) rating scale: "In the following section, you will read a list of difficult words. These words are rare, so you may find some to be difficult to comprehend. Please carefully rate the familiarity of each word in the following list. The rating scale is from 1 (very un- familiar) to 5 (very familiar)." The average familiarity rating scores was 1.3 (out of 5; 5-most familiar), ranging from 1.19 to 1.34 across target letters and target positions. One-way ANOVAs with the factor target position shows no significant differences in familiarity ratings across target letter positions (by-subject: $p > 0.05$, by-item: $p > 0.05$). The average pronounceability rating scores was 3.64 (out of 5; 5-with ease), ranging from 3.32 to 3.98 across target letters and the target positions. One-way ANOVAs with the factor target position reveals no significant differences in pronounceability rating scores across target letter positions (by-subject: $p > 0.05$, by-item: $p > 0.05$). (See Table 5.6).

5.7.5 Data Analysis

Analyses used for pseudowords were identical to those for Experiment 5, including the two-way Analyses of variance (ANOVAs) with fixation position and target location, linear trend analyses with fixation position and target location, Point-to-Point Distance method for visual field asymmetry, and mixed linear regression.

Table 5.4: Stimulus factors controlled for in Experiment 6, with means and standard error of the mean (SEM) information.

A. Orthographic Neighborhood Frequency	Target Position				
Target Letter	1	2	3	4	5
l	6.60 (0.23)	6.94 (0.35)	6.54 (0.35)	6.85 (0.31)	6.73 (0.23)
n	7.80 (0.24)	7.65 (0.34)	6.89 (0.34)	7.08 (0.35)	6.71 (0.24)
r	7.36 (0.25)	7.38 (0.34)	6.61 (0.35)	6.18 (0.33)	7.03 (0.22)
t	6.56 (0.24)	7.46 (0.34)	6.79 (0.37)	6.65 (0.30)	6.40 (0.25)

B. Number of Bigram.	Target Position				
Target Letter	1	2	3	4	5
l	2217 (180)	2929 (176)	2473 (192)	2287 (154)	2098 (152)
n	2487 (249)	2530 (243)	3827 (279)	3656 (270)	3857 (230)
r	2846 (221)	2904 (218)	2993 (284)	3318 (269)	3252 (240)
t	2747 (180)	4056 (164)	3187 (264)	3862 (352)	2569 (119)

C1. Number of counts	Letter position within a word that has been changed				
Target Letter	1	2	3	4	5
l	20	20	21	19	20
n	22	18	21	20	19
r	23	18	21	21	18
t	22	19	20	20	18

C2. Number of counts	Letter position within a word that has been changed				
Target Letter Position	1	2	3	4	5
1	--	18	21	23	18
2	23	--	17	21	19
3	21	17	--	22	20
4	21	20	21	--	18
5	22	20	24	14	--

Table 5.5: (Table 5.4 Continued) Stimulus factors controlled for in Experiment 6, with means and standard error of the mean (SEM) information.

D. Orthographic Neighborhood Size

	Letter position within a word that has been changed				
Target Letter	1	2	3	4	5
l	3.05 (0.52)	2.74 (0.50)	1.95 (0.34)	1.58 (0.19)	2.20 (0.35)
n	1.64 (0.24)	2.22 (0.32)	2.48 (0.39)	2.65 (0.33)	2.79 (0.39)
r	2.48 (0.38)	3.28 (0.58)	2.55 (0.40)	2.53 (0.48)	2.44 (0.32)
t	3.50 (0.53)	2.74 (0.55)	2.86 (0.48)	2.35 (0.37)	2.06 (0.40)

E.Orthographic Neighborhood Frequency

	Letter position within a word that has been changed				
Target Letter	1	2	3	4	5
l	27.81 (14.39)	6.33 (1.94)	4.44 (1.67)	8.82 (2.47)	5.37 (1.53)
n	7.40 (1.74)	6.65 (1.31)	9.10 (2.86)	12.27 (4.18)	7.44 (1.48)
r	13.17 (4.00)	8.39 (2.92)	8.21 (2.09)	13.80 (4.12)	8.34 (1.72)
t	15.54 (4.54)	10.20 (2.86)	8.95 (2.24)	13.80 (4.12)	8.97 (1.72)

F. Number of Bigrams

	Letter position within a word that has been changed				
Target Letter	1	2	3	4	5
l	2416 (166)	2208 (133)	2254 (161)	2455 (227)	2696 (198)
n	3775 (220)	3622 (288)	3134 (278)	2869 (309)	2943 (295)
r	3061 (295)	3155 (249)	3005 (232)	3142 (272)	2957 (186)
t	3507 (259)	2771 (270)	3247 (273)	3256 (247)	3586 (297)

G.*Number of Bigram (based on every two letter positions in a word)*

Target Letter	1-2	2-3	3-4	4-5
l	559 (71)	570 (75)	712 (77)	561 (75)
n	714 (106)	834 (128)	831 (134)	892 (148)
r	657 (81)	728 (119)	856 (128)	822 (133)
t	947 (114)	854 (113)	706 (86)	777 (97)

Table 5.6: Offline tests in Experiment 6, with means and standard error of the mean (SEM) information.

Pronounceability ratings			Target Position		
Target Letter	1	2	3	4	5
l	3.90 (0.23)	3.98 (0.22)	3.69 (0.24)	3.84 (0.24)	3.90 (0.23)
n	3.32 (0.25)	3.38 (0.25)	3.73 (0.27)	3.57 (0.27)	3.32 (0.25)
r	3.33 (0.26)	3.55 (0.28)	3.66 (0.27)	3.58 (0.27)	3.33 (0.28)
t	3.65 (0.28)	3.74 (0.28)	3.79 (0.23)	3.77 (0.23)	3.65 (0.24)

Familiarity ratings			Target Position		
Target Letter	1	2	3	4	5
l	1.34 (0.12)	1.31 (0.13)	1.19 (0.10)	1.32 (0.15)	1.34 (0.12)
n	1.32 (0.13)	1.30 (0.12)	1.51 (0.15)	1.30 (0.12)	1.32 (0.13)
r	1.32 (0.12)	1.26 (0.12)	1.25 (0.11)	1.34 (0.14)	1.32 (0.13)
t	1.24 (0.12)	1.25 (0.12)	1.31 (0.14)	1.29 (0.13)	1.24 (0.13)

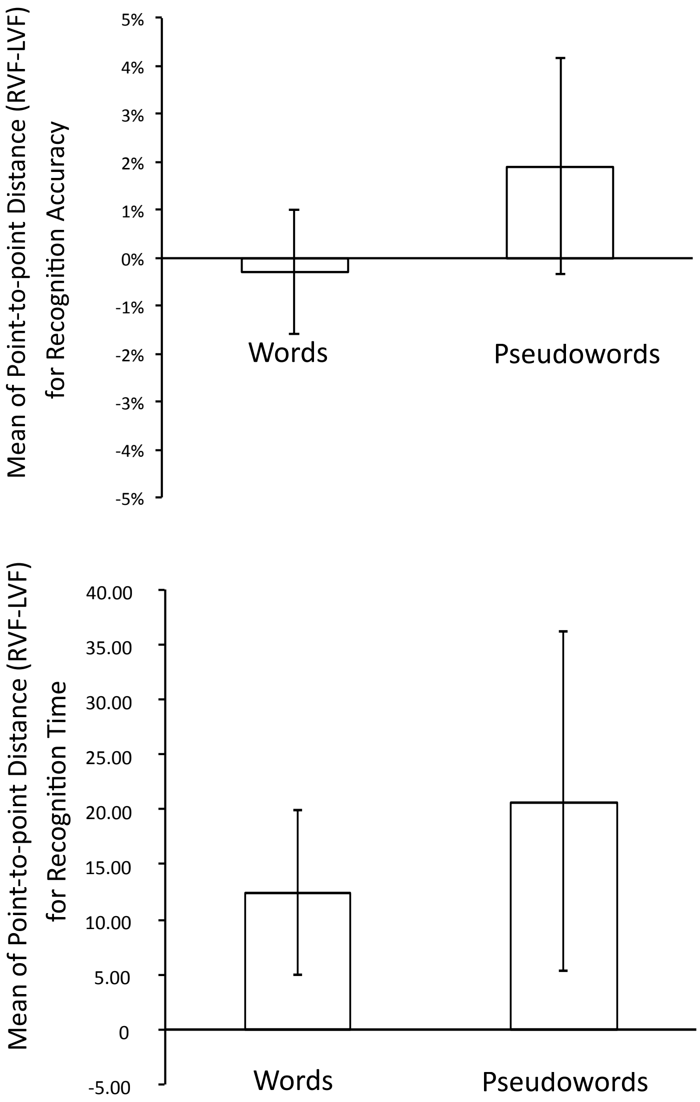


Figure 5.4: Similarity measure between visual fields for two stimulus types in Experiments 5-6: data points are from fixations at the two extreme letters. Neither words nor pseudowords show significant recognition asymmetry. Top panel, recognition accuracy. Bottom panel, reaction times. Positive values indicate RVF superiority while negative values indicate LVF superiority.

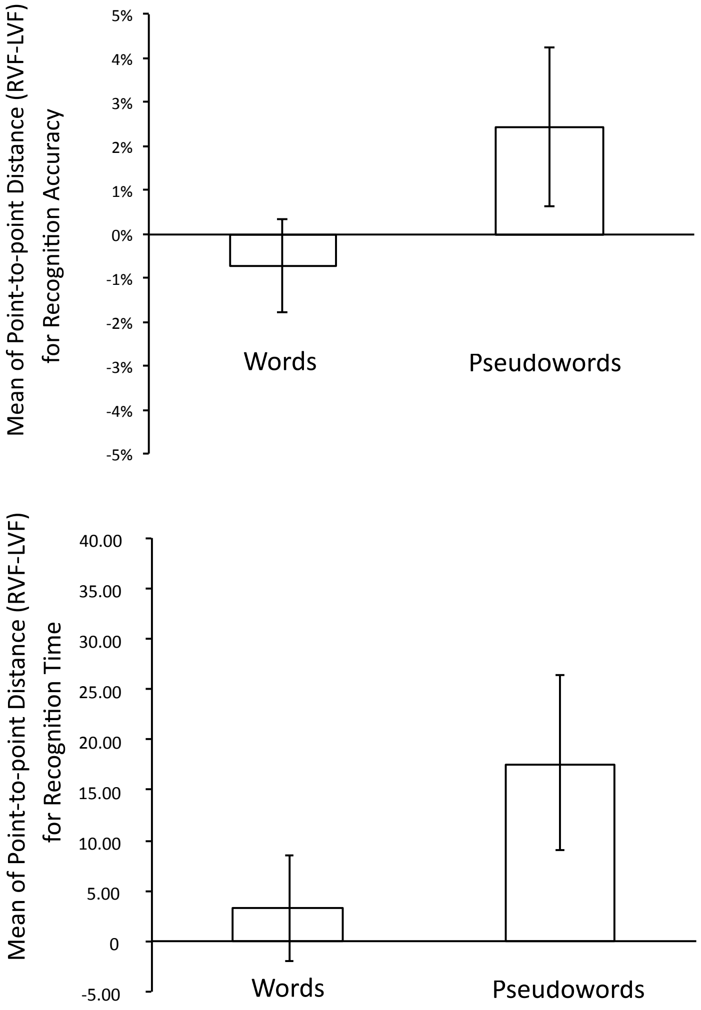


Figure 5.5: Similarity measure between visual fields across two types of stimuli in Experiments 5-6: all data points are included. Pseudowords show significant recognition superiority in the RVF. By contrast, words do not demonstrate recognition asymmetry, nor a VF superiority effect. Top panel, Recognition accuracy. Bottom panel, Reaction times. Note that positive values indicate RVF superiority while negative values indicate LVF superiority.

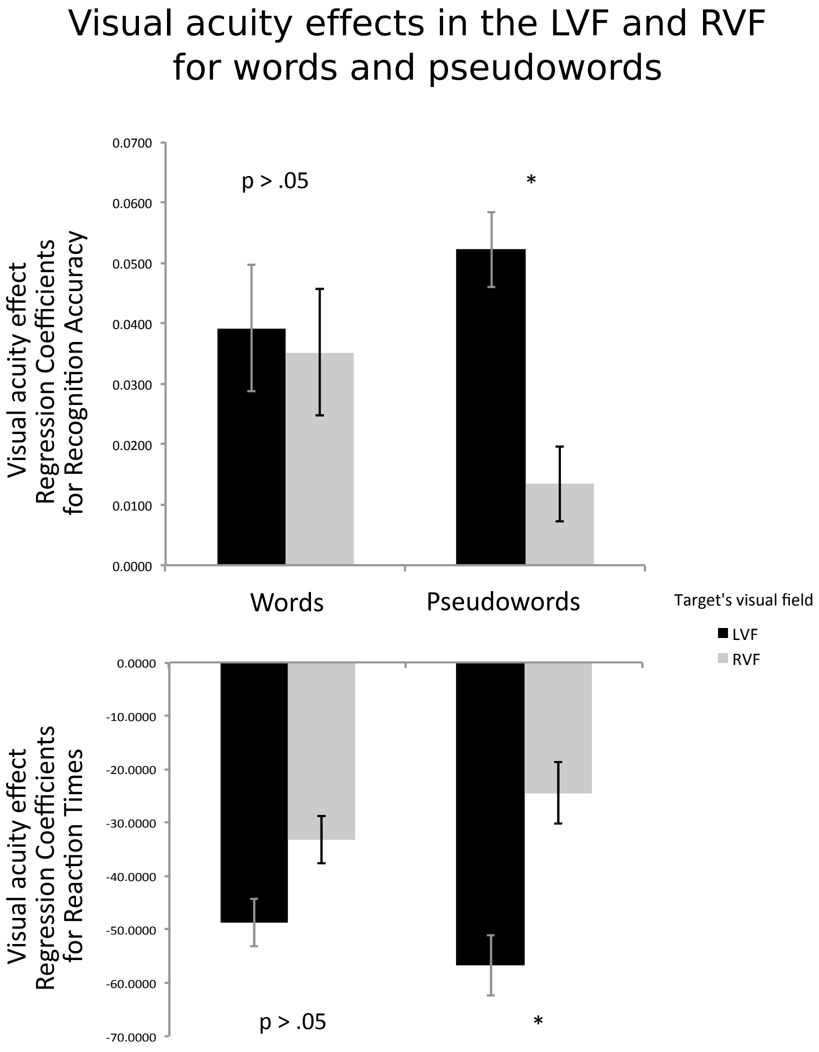


Figure 5.6: Regression coefficients of the visual acuity effect in the LVF and RVF in Experiments 5-6. For pseudowords, there is a larger distance effect (visual acuity effects) for target recognition in the LVF than the RVF. By contrast, target recognition for words demonstrates equally significant visual acuity effects in both visual fields. Recognition accuracy (top panel) and reaction times (bottom panel). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

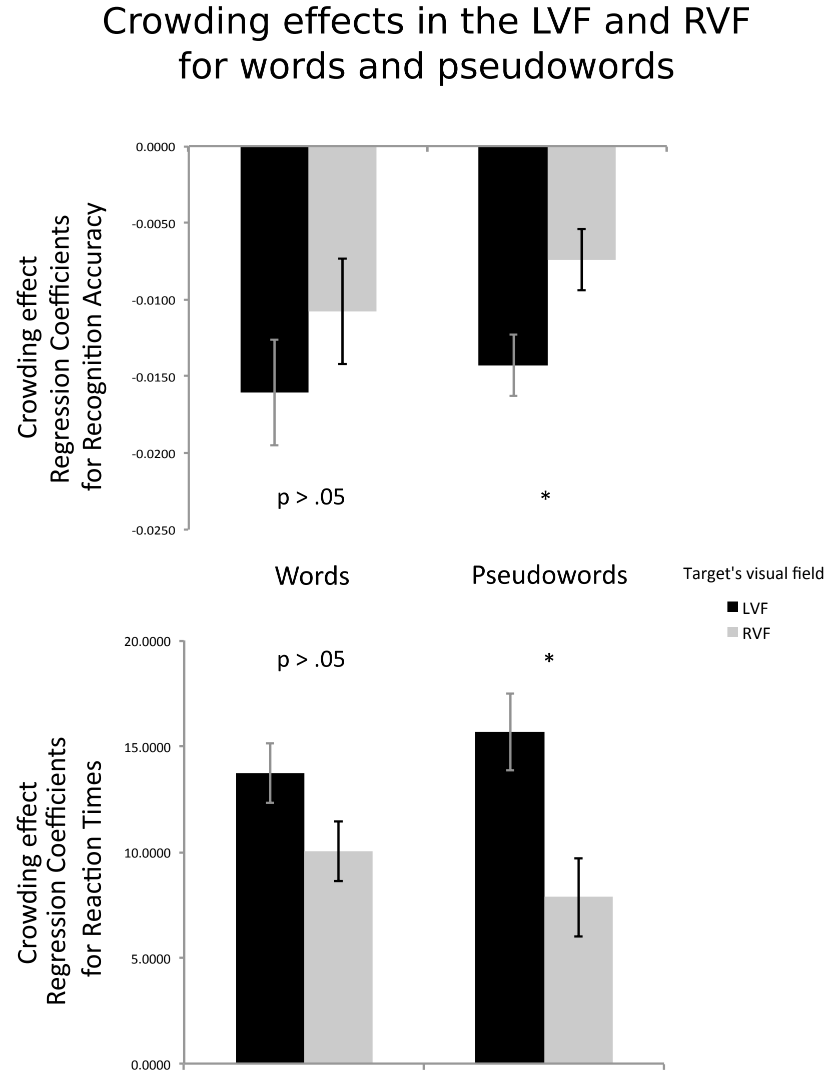


Figure 5.7: Regression coefficients of crowding effect in the LVF and RVF in Experiments 5-6. For pseudowords, the crowding effect is significantly larger in the LVF than RVF. This may lead to the crowding asymmetry between the visual fields for pseudowords. By contrast, words demonstrate equally significant crowding effects in both visual fields, with crowding asymmetry between the visual fields. Recognition accuracy (top panel) and reaction times (bottom panel). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5.8 Results

Analyses of variance (ANOVAs). The main effect of fixation position is significant (Accuracy: F (4, 76) = 18.36, $p < 0.0001$; RTs: F (4, 76) = 15.58, $p < 0.0001$). Tukey post-hoc analysis shows that recognition accuracy is significantly higher when fixation is at the third letter than the first letter ($p < 0.05$) or the last letter ($p < 0.005$), as well as at the second letter compared to the last letter (See Figure 5.8). The main effect of target position is also significant for the RTs(Accuracy: $p > 0.1$; RTs: F (4, 76) = 6.38, $p < 0.0005$). Tukey post-hoc analysis of target location, however, does not indicate any significant accuracy differences between any pair of positions (See Figure 5.9). There is a significant interaction between fixation position and target position (Accuracy: F (16, 304) = 3.21, $p < 0.0001$ RTs: F (16, 304) = 1.74, $p < 0.05$). Multiple comparison tests reveal that when the target is in the first half of the pseudoword (1-2 out of 5), performance is worst (lowest recognition accuracy and longest reaction times) for fixations at the last letter. When the target letter is in the second half of the pseudoword (4-5 out of 5), performance is generally worse for fixations at the first letter compared to any other position.

Linear and quadratic trend analyses with fixation position and target location. Recognition probability averaged over all possible target position varies as a function of initial fixation position with a marginal linear trend (Accuracy: t (79) = - 1.94, p = 0.0558; RT: t (79) = 1.97, p = 0.0516), and a significant quadratic trend (Accuracy: t (79) = - 7.91, $p < 0.0001$; RTs: t (79) = 7.29, $p < 0.0001$). See Figure 5.8. There is neither a significant linear trend for target position (Accuracy: $p > 0.1$; RTs: $p > 0.1$), nor a significant quadratic trend (Accuracy: $p > 0.1$; RTs: $p > 0.1$). See Figure 5.9.

Similarity measure between the two visual fields: point-to-point distance. The similarity measure shows no differences in recognition performance (accuracy and RTs) between the two visual fields. This performance similarity holds for analyses based on the whole dataset (Accuracy: t (19) = -0.89 p > 0.1; RTs: t (19) = - 1.56, p = 0.06, marginal) and the subset with fixations at the first vs last letters (Accuracy: t (19) = - 0.24, p > 0.1; RTs: t (19) = - 0.87, p > 0.1). See Figure 5.4 and Figure 5.5.

Linear Mixed Regression. Our results show that both visual acuity and crowding contribute to recognition performance for the target discrimination for pseudowords in the viewing position paradigm (See Table 5.3). The contribution of visual acuity manifests as a typical distance-from-fixation effect: as the target letter goes farther from fixation, accuracy decreases and RTs increase. The contribution of crowding show that the impact of this distance-from-fixation effect increases with the number of characters in the target's visual field. Moreover, there are visual field differences revealed by the visual acuity asymmetry and crowding asymmetry between the two visual fields. There are more pronounced visual acuity and visual crowding effects for target recognition in the LVF than the RVF (See Figure 5.6 and Figure 5.7).

Summary of Main Results

The VP curve for pseudowords is asymmetric, with the better performance at the beginning than at the end. Performance for target letters in the LVF and RVF, however, do not significantly differ. Both visual acuity and crowding contribute to the overall letter recognition pattern. There is a visual acuity asymmetry and a crowding asymmetry between the two visual fields: both visual acuity effects and crowding effects are significantly larger in the LVF than the RVF.

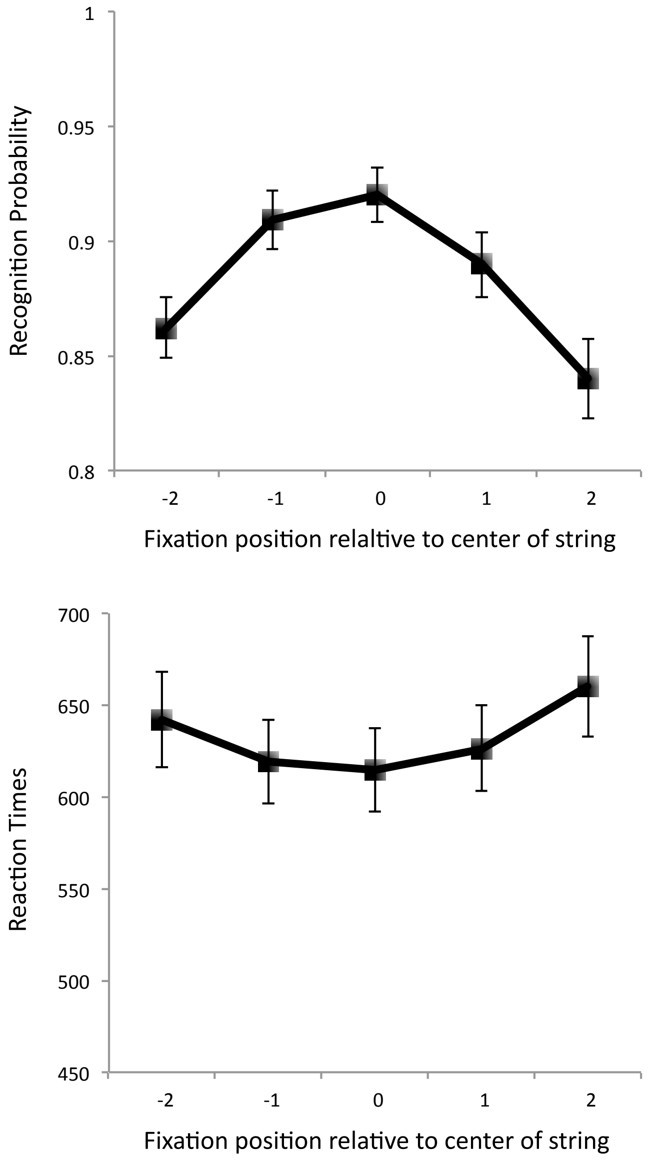


Figure 5.8: Two VP curves for recognition accuracy and reaction times for pseudowords. Note the asymmetric beginning vs end viewing position effect for pseudowords: letter recognition is more accurate and faster when eyes initially fixate the beginning of a non-word letter string. Top panel, recognition accuracy of correct symbol recognition as a function of fixation position, collapsed across target positions. Bottom panel, recognition times of correct symbol recognition as a function of fixation position, collapsed across target positions.

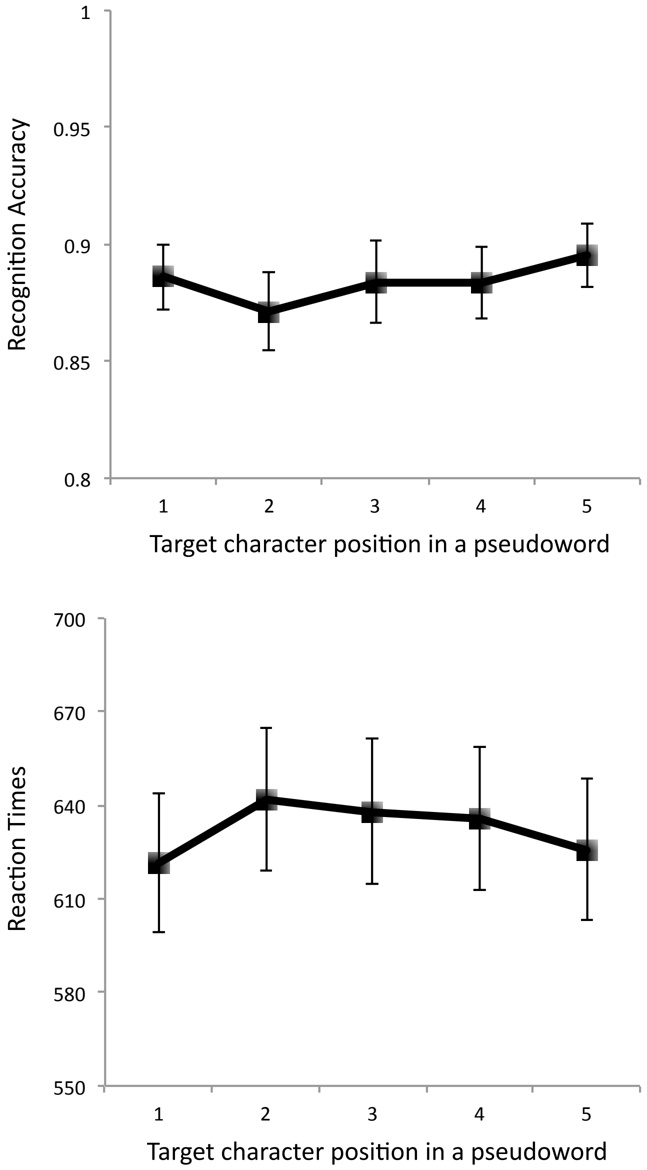


Figure 5.9: Target letter position function for pseudowords. Quadratic but no linear trends suggest recognition benefits for the two extreme target locations; no initial symbol benefit is found. Top panel, recognition accuracy of correct character recognition as a function of target letter position, collapsed across target positions. Bottom panel, reaction times of correct character recognition as a function of target letter position, collapsed across target positions.

5.9 Discussion

The present study was designed to explore VP effects for words and pseudowords in a target discrimination task within a viewing position paradigm. We especially focused on the left-of-center OVP asymmetry as we had not observed it for any of the non-word/non-letter stimulus strings that we had used across a number of experiments, leading us to hypothesize that it might be word specific. Furthermore, to evaluate the extent to which mechanisms proposed by the perceptual learning account can account for the VP patterns for words and pseudowords, we analyzed the detailed visual field (a)symmetries in letter recognition and visual crowding.

In broad strokes, the VP curve for pseudowords and words are similar. For both, the VP curve - performance as a function of fixation location - has an inverted U-shape: performance decreases as a fixation moves toward the more extreme letters of a word/pseudoword, with a greater drop for a fixation at the end than at the beginning of the word (i.e., beginning vs end asymmetry VP effect).

There are, however, several differences, in the VP curves for words and pseudowords. First, the locus of OVP for pseudowords is at the center position while for words it is at the center-to-left position. In other words, the OVP is symmetric for pseudowords but asymmetric for words. Only for words do we see an asymmetric OVP – i.e., that fixating the second letter of a 5-letter word leads to the highest letter recognition accuracy and shortest RTs compared to fixations at any other positions in a word. The OVP for pseudowords is at its center, similar to that observed for nonword stimuli. Second, the beginning vs end VP effect for pseudowords indicates a processing benefit for fixations at the pseudoword's beginning, regardless of where the target letter is within the pseudoword. In other words, target position within a pseudoword (just as for non-word letter strings and non-letter symbol strings) does not modulate the recognition performance. By contrast, the locus of target letter position within a word does modulate letter recognition performance. Target letters appearing in the initial part of words are better recognized those at its end regardless of fixation position in a word. It is likely that this initial position advantage contributes to the distinctive VP pattern for words compared to that for any other stimulus strings. As the letter recognition is best at the word initial position, fixating the first or second letter makes it even easier to recognize letters at those positions. Alternatively, while fixating the first or second letter, the relatively effortless processing for initial letters may benefit processing for the remaining letter positions; consequently, a target at one of these remaining positions may benefit from the overlap of fixation position with the initial letter advantage. Taken together, the asymmetric OVP for words seems to suggest that the center-to-left OVP asymmetry may be specific to words.

Although the asymmetric OVP seems to be word specific, we have consistently observed the beginning vs end asymmetric VP effect – for words as well as other letter and letter-like strings. We have shown that this asymmetric VP effect can be accounted for in terms of perceptual learning. Better letter recognition in the RVF and greater visual crowding effects in the LVF are consistently found with letter and letter-like strings that demonstrate the beginning vs end VP effect. If perceptual learning accounts for at least the asymmetry of beginning vs end VP effect, there should be a perceptual asymmetry between the two visual fields in letter recognition and in visual crowding. Our analysis for pseudowords shows a crowding asymmetry between the visual fields. The effect of crowding is larger in the LVF than in the RVF, consistent with the proposal that the asymmetry of VP effect could be due to the perceptual asymmetry.

However, perceptual asymmetry is not observed for words. There are no indications of perceptual asymmetry in letter recognition for words; there are no visual field differences either in letter recognition (Figure 5.4 and Figure 5.5), visual acuity (Figure 5.6) or visual crowding (Figure 5.7). This absence of visual crowding asymmetry for words places limits on a perceptual learning account of the beginning vs end VP asymmetry. In our opinion, this finding does not rule out the perceptual asymmetry contribution to the beginning vs end VP effect. Rather, it implies the involvement of at least one additional mechanism. The absence of a visual crowding asymmetry for words likewise suggests additional processes that may be specific to words. Whatever these processes, they seem to decrease the crowding effect in the LVF. We also find the initial position advantage only for words in this series of experiments; this boosts target recognition in the LVF since stimulus initial letters appear mostly in the LVF within the viewing position paradigm. Our finding of the initial position advantage for words can account for no visual field differences in letter recognition: it is likely that the crowding effect in the LVF, similarly, is diminished since letter recognition for words in the LVF is generally better than that for pseudowords or other non-word stimuli.

If the initial position advantage reflects some additional process specific to words that contributes to the asymmetric OVP and beginning vs end VP effect together with perceptual asymmetry, then what might this candidate mechanism(s) be? Here we look to the lexical properties of our experimental stimuli for possible explanations. Our word and pseudoword stimuli were both matched across target positions on orthographic neighborhood frequency and number of bigrams, as well as frequency for words. However, there was a tendency for orthographic neighborhood size to be slightly larger for targets at the initial letter positions in a word (See Table 5.1B). Since larger neighborhood size seems to facilitate recognition (V. J. Laxon, Coltheart, & Keating, 1988; V. Laxon, Masterson, & Moran, 1994; Andrews, 1997), it is likely that the relatively larger neighborhood size for words with a target at the initial position is captured in the initial position advantage for words. If this is the case, it suggests a potential impact of letter context on VP effects for words. This may also suggest that the initial position advantage, which may contribute to the absence of perceptual asymmetry, does not reflect processing specific to words, but rather processing contributions of sublexical to lexical factors. On the other hand, the distribution of orthographic neighborhood sizes over target positions (See Table 5.1B) does suggest that these sublexical to lexical processes may not be able to explain much of the asymmetric OVP that we find for words only. Taken together, we tentatively propose that the distinctive VP curve for words, including the asymmetric OVP as well as the beginning vs end asymmetric VP effect, given no evidence of perceptual asymmetry, can be attributed to mechanisms associated with sublexical to lexical processing as well as those specific to word level processing.

5.10 Conclusion

We replicated the known center-to-left asymmetric OVP effect for words in our letter discrimination task within a viewing position paradigm. Pseudowords, by contrast, did not show an asymmetric OVP effect. Our findings thus suggest that the asymmetric OVP effect might be word specific. The absence of visual crowding asymmetry for words suggests limits on the perceptual learning account of the beginning vs end VP asymmetry due to a perceptual asymmetry between the visual fields. We tentatively propose that sublexical and lexical analyses employed during word processing also might contribute to the observed beginning vs end asymmetric VP effect for word and pseudowords. The asymmetric beginning vs end VP effects observed for non-word letter and letter-like strings, by contrast, could be a pure reflection the perceptual asymmetry (without the sublexical or lexical contributions), consistent with the perceptual learning account.

5.11 Acknowledgement

We thank Anna Chen for assistance in collecting data for Experiment 6. This research was supported in part by a fellowship from the Taiwan MOE Graduate Fellowship in Cognitive Neuroscience to W.C. Chapter 5, in part, is currently being prepared for submission for publication of the material. The dissertation author was the primary investigator and author of this material. Wen-Hsuan Chan; Thomas P. Urbach; Marta Kutas. The dissertation author was the primary investigator and author of this material.

5.12 Appendix C

Table 5.7: Experimental stimuli used in Experiment 5 (part1)

Target Letter	Target Position				
	1	2	3	4	5
n	naive	anise	bingo	agony	ashen
	nosey	anode	bonus	amend	aspen
	naked	unify	manic	chink	bacon
	naves	envoy	dingy	chunk	chain
	necks	gnash	candy	hyena	deign
	nexus	gnome	funky	ebony	divan
	newsy	gnaws	fungi	downy	demon
	nymph	index	genus	guano	cumin
	niche	unwed	handy	hound	feign
	nicks	knead	hanky	hymns	sedan
	nodes	knobs	jingo	meany	mason
	nomad	knife	ounce	piano	basin
	named	snack	panic	shine	bison
	napes	snake	bench	swing	cabin
	nosed	sneak	pinky	scone	spawn
	noisy	snipe	punch	spank	sudan
	novas	unzip	boned	eying	vegan
	nudge	endow	sonic	opine	waken
	nudes	enjoy	bunch	fiend	widen
	numbs	inked	windy	wound	wagon
r	racks	brake	marsh	adore	abhor
	raise	brisk	mercy	afire	boxer
	raked	crisp	cargo	azure	buyer
	rapid	crush	carve	beard	choir
	razed	crude	curve	chirp	cigar
	rabid	wrack	acrid	chord	decor
	recap	drags	forge	decry	demur
	ricks	bravo	gyros	dowry	favor
	rebus	grape	jerky	fibre	foyer
	repay	grimy	murky	fiery	shear
	rhyme	grief	derby	hydra	humor
	rocky	gravy	porch	ivory	joker
	rogue	brush	purge	opera	mayor
	rides	creak	hardy	wharf	poker
	roach	probe	scrap	query	scour
	robes	proxy	scrub	scarf	usher
	rouge	prize	spray	shark	spear
	rowdy	prose	syrup	shirk	swear
	ridge	freak	virus	weird	vapor
	risky	urges	wordy	zebra	vicar

Table 5.8: Experimental stimuli used in Experiment 5 (part2)

Target Letter	Target Position				
	1	2	3	4	5
t	thief	atoms	acted	acute	adept
	thump	ethic	botch	amity	adopt
	thyme	ethos	ditch	chute	bigot
	tacks	itchy	fetch	couth	cheat
	tacky	items	fetid	deity	covet
	tamed	stack	fetus	gifts	debit
	taxis	stagy	gutsy	gusto	duvet
	teach	staid	matey	misty	evict
	tempo	stake	motif	mufti	facet
	tepid	stamp	muted	peaty	ghost
	ticks	stave	cotes	piety	moist
	tides	stead	optic	quota	pivot
	timed	steak	patio	skate	posit
	tipsy	steam	pitch	spate	scout
	toads	stoic	bathe	suite	shout
	topic	stoke	baths	depth	squat
	toxic	stomp	myths	vesta	swift
	tubes	stove	pithy	vista	vomit
	tweak	stump	withy	sixth	yacht
	typed	steph	votes	width	yeast
l	lacks	album	aglow	aisle	afoul
	lambs	blush	balmy	ample	awful
	lapse	gleam	belay	bugle	basil
	lauds	bleak	belch	cable	bowel
	leach	clasp	bilge	chalk	cavil
	leafy	cloak	halve	coils	devil
	leaky	elbow	bulge	dimly	hazel
	limbo	flake	bulky	fable	focal
	limbs	flock	delay	gaily	ghoul
	limey	aloud	filed	godly	shawl
	lobes	clash	filmy	guild	hovel
	lodge	glide	mulch	shelf	medal
	lousy	globe	oiled	imply	pedal
	lowed	plumb	palsy	qualm	quail
	lucid	blaze	pulse	sadly	scowl
	lucky	plead	salve	scald	sibyl
	lumps	pluck	solid	scalp	spoil
	lumpy	slimy	splay	scold	vocal
	leash	olive	sulky	wield	vowel
	lymph	slick	valid	yield	yodel

5.13 Appendix D

Table 5.9: Experimental stimuli used in Experiment 6 (part1)

Target Letter	Target Position				
	1	2	3	4	5
n	naige	anive	bingy	afony	aphen
	nasey	anofe	bonup	amind	acpen
	naxed	unigy	manif	phink	bacin
	navex	envox	dinvy	chund	whain
	necis	gnase	jandy	hymna	deian
	nequs	gnomy	fungy	evony	dipan
	nefsy	enaws	funzi	cowny	dumon
	nymps	invex	gynus	guand	qumin
	nicye	unjed	hanby	hounk	feian
	nioks	unead	hanfy	hyens	sedyn
	nydes	anobs	jengo	feany	mazon
	nowad	knixe	ounch	piane	jasin
	nimed	snacy	janic	shinp	bivon
	napew	snike	pench	swink	cazin
	nised	snoak	pindy	smone	skawn
	noivy	knipe	ponch	smank	qudan
	novam	unzik	joned	exing	vecan
	nadge	endox	xonic	opune	waden
	nuves	anjoy	banch	wiend	viden
	numks	inzed	wondy	jound	wigon
r	racus	prake	mersh	ajore	achor
	raige	brish	merdy	abire	boxar
	rekew	grisp	curgo	aqure	quyer
	ropid	crish	jarve	bearp	phoir
	ryzed	cruke	corve	chorp	cifar
	rabig	drack	acrib	chorm	devor
	recas	draus	forve	debry	hemur
	rieks	bravy	cyros	dogry	kavor
	rejus	graxe	jervy	fiury	foger
	recay	grify	murzy	hiery	siear
	rhype	srief	derfy	hybra	qumor
	rocey	grivy	jorch	ibory	jover
	roque	bruch	qurge	spera	jayor
	ridew	cresk	harcy	whard	poyer
	roacs	proge	scraw	vuery	swour
	rybes	prexy	scruz	smarf	ushor
	rhuge	mrike	sprad	sharf	skear
	rowby	prosh	sorup	chirk	swoar
	rudge	froak	virux	geird	vahor
	risey	urgey	zordy	hebra	vixar

Table 5.10: Experimental stimuli used in Experiment 6 (part2)

Target Letter	Target Position				
	1	2	3	4	5
t	thieb	atums	actud	acite	adect
	thumd	othic	hotch	adity	adost
	thype	athos	gitch	chate	bugot
	tacus	itshy	getch	coath	chept
	tasky	atems	fetiz	veity	coket
	tamex	itack	feths	gefts	gebit
	tuxis	staby	qutsy	qusto	dufet
	teash	staim	matex	zisty	exict
	temfo	stade	motis	musti	facut
	tewid	stamb	quted	peoty	whost
	tecks	stame	xotes	pioty	voist
	tidek	steud	optiz	quoty	pizot
	tived	steaf	putio	smate	pozit
	tiksy	stoam	petch	spath	smout
	thads	atoic	bythe	swite	whout
	tozic	styke	jaths	cepth	skuat
	towic	atomp	mytis	hesta	swict
	tubis	stode	pethy	viste	vofit
	theak	stumk	zithy	bixth	yocht
	typew	stech	votex	wadth	deast
l	lecks	alqum	aglof	aible	amoul
	lembs	blash	bilmy	asple	adful
	lopse	bleam	belaq	jugle	jasil
	lamds	blesk	bulch	cuble	bozel
	leacy	clisp	vilge	chals	cahil
	leady	cloag	halde	joils	qevil
	lecky	elbox	bulce	dibly	dazel
	limpo	flade	bulzy	jable	fomal
	limks	floce	delap	maily	phoul
	libey	floud	filad	gofly	scawl
	lobew	glash	falmy	fuild	hozel
	ludge	glive	qulch	smelf	wedal
	louby	gloce	ciled	implo	jedal
	loxed	plamb	palsh	quilm	quawl
	lucix	plaze	pilse	sagly	smowl
	lusky	pleak	salce	spald	sibal
	lumph	plick	solix	scalg	swoil
	lumsy	slify	sploy	spold	vocil
	leysh	slive	qulky	wiely	vobel

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Chapter 6

Do visual field processing asymmetries in the parafovea extend to the processing in the fovea? Hemispheric asymmetry in foveal and parafoveal processing

6.1 Abstract

Visual half-field studies have shown that words are more easily recognized when presented in the right visual field (RVF) than the left visual field (LVF); this is known as the RVF advantage. Words presented foveally likewise are recognized faster and more accurately when presented to the right than left side of fixation; this is known as the (right vs left asymmetric; beginning vs end) viewing position (VP) effect. According to the cerebral laterality account these two effects are both a consequence of the left hemisphere (LH) dominance for language. We use ERPs to test two assumptions of the cerebral laterality account: namely, that (1) the same mechanisms underlie the visual field differences within and outside the fovea; in other words, that there is a processing continuity for words within and outside the fovea. (2) the RVF advantage in the fovea is a consequence of LH specialization for language.

ERPs were recorded to stimuli (non-word letter strings) presented in each of the visual fields - either parafoveally (as a proxy for the RVF advantage) or foveally (as a proxy for the VP curve asymmetry). For both foveal and parafoveal lateralized stimuli, inter-hemispheric transfer times are faster for RH-to-LH transfer than LH-to-RH transfer as inferred from P1 and N190 measures, consistent with better behavioral performance for stimuli to the right than left side of fixation. The occipital N190 to lateralized stimuli in the foveal is in general shorter in latency and larger in amplitude than that to lateralized stimuli outside the fovea; however, these differences are larger in the RVF than LVF. This pattern of results cannot be explained by the processing continuity assumption if LH specialization for language is the responsible mechanism. Consistent with this conclusion, we also find larger amplitude reductions for transfer from the RH-to-LH than vice versa, implicating factors other than left hemisphere dominance for language in observed hemispheric differences. Taken together, our findings do not support the cerebral laterality account of the beginning vs end/ right vs left asymmetry of the (foveal) VP effect.

6.2 Introduction

Visual word recognition strongly depends on the position in a word where the reader's eyes fixate. Research has shown that word recognition is faster and more accurate when fixating the beginning than the end of a word; this phenomenon is known as the asymmetric (beginning vs end) viewing position (VP) effect (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984).

Some researchers account for this processing asymmetry with word-specific brain mechanisms. One such account – the cerebral laterality hypothesis (Brysbaert, 1994; Brysbaert, Vitu, & Schroyens, 1996) attributes this particular VP curve asymmetry to left hemisphere specialization for language (especially word processing). The cerebral laterality account is influential in large part because other proposals cannot fully explain the beginning vs end asymmetry of the VP curve. For example, the informativeness account (O'Regan et al., 1984; Clark & O'Regan, 1999) attributes the processing benefit for a fixation at the beginning of a word to the greater information that region provides regarding the word's identity. This account, however, falls short, because it cannot explain the absence of an end benefit for words in which the end is more informative (Brysbaert, 1994), implying some missing factor. Likewise, the perceptual learning account (Nazir, O'Regan, & Jacobs, 1991; Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998; Aghababian & Nazir, 2000), on which the VP curve asymmetry is a consequence of retinal training for words during reading, successfully predicts a shift in the asymmetry of the VP curve given experience with a different reading direction (Farid & Grainger, 1996), but also falls short of explaining why the curve merely becomes more symmetric rather than asymmetric in the reverse direction. The symmetric pattern leaves the possibility that left hemisphere specialization for language (word) processing – as proposed by the cerebral laterality account - also may play at least a partial role in the VP curve asymmetry.

According to the cerebral laterality account, words to the right side of fixation are treated as if they were positioned in the right visual field (RVF), wherein lexical information directly projects to the left hemisphere (LH). Words in the RVF are easier to process (RVF advantage) presumably because the left hemisphere is the language dominant hemisphere for the majority of right and left handed people. The cerebral laterality account further maintains that because the left hemisphere is language dominant information in the right hemisphere must be transferred to the left hemisphere before word processing can begin (Haegen & Brysbaert, 2011; Haegen, Brysbaert, & Davis, 2009; McCormick, Davis, & Brysbaert, 2010; Whitney, 2001). When fixating the beginning of a word, the rest of the word is positioned to the right of fixation, projecting directly to the LH without the need for inter-hemispheric transfer. By contrast, fixating the end of a word positions the rest of the word in the left visual field, and thus requires inter-hemispheric transfer from the RH to the LH. It is this inter-hemisphere transfer from the RH to the LH that leads to the worse performance at a word's end as reflected in the asymmetric beginning vs end VP effect.

Brysbaert (1994) compared the VP curve asymmetry for individuals with typical (left) hemisphere language dominance to those with atypical (right) hemisphere language dominance. If inter-hemispheric transfer is a pre-requisite for processing words at the fovea, then individuals with atypical (right) hemisphere language dominance should exhibit VP curve shifted to the right (toward the end of word) compared to the typical left-shifted VP curve. They did find a small but reliable group difference in the predicted direction, and concluded that the VP curve asymmetry reflects inter-hemispheric transfer for words in the fovea, which is akin to the RVF advantage seen for words in the parafovea. In other words, the apparent RVF advantage for words in both the fovea and the parafovea are presumed to be a consequence of left hemisphere dominance for language.

One, however, may question whether this conclusion follows unequivocally from the finding of the (relatively) right-shifted VP curve for individuals with atypical brain organization for language. Factors other than hemispheric dominance for language also may yield the same (relatively) right-shifted VP curve. For instance, attention biases the visual field contralateral to the hemisphere that is more strongly activated (Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990; Behrmann, Ebert, & Black, 2004). The different VP curves for individuals with typical vs atypical brain lateralization for language thus may reflect hemispheric attentional biases rather than hemispheric dominance for word processing. Moreover, the argument that the (leftward) VP curve asymmetry reflects left hemispheric dominance for word processing is also questionable. A leftward bias in a line-bisection task, for example, has been linked to right hemisphere activation (Bowers & Heilman, 1980; Billingsley, Simos, Sarkari, Fletcher, & Papanicolaou, 2004; Çiçek, Deouell, & Knight, 2009; Fink et al., 2000; Fink, Marshall, Weiss, & Zilles, 2001; Fink, Marshall, Weiss, Toni, & Zilles, 2002; Flöel et al., 2002; Marshall, 1997). Perhaps, the leftward VP curve likewise reflects right hemisphere activation and not inter-hemispheric transfer to the left hemisphere for word processing. Such alternatives undermine the conclusion that inter-hemispheric transfer costs necessarily account for worse recognition performance at a word's end.

The assumption of the cerebral laterality account that the VP curve asymmetry (in the fovea) depends on the same mechanism as the RVF advantage (in the parafovea), moreover, is not out of question. In a traditional visual hemi-field (VHF) paradigm, words are presented lateral to fixation in the parafovea; the RVF advantage is well established through the VHF paradigm. It is unclear, however, whether the mechanisms underlying the RVF advantage applies to the processing of words in the fovea. Although the asymmetric VP curve suggests a processing benefit while the most part of a word is presented in the right side of fixation, it is an open question on whether the same mechanisms of "RVF advantage in the fovea" underlie the RVF advantage in the parafovea. The concern mainly results from a debate regarding fovea processing. It has been a debate on whether the information projects in the fovea is split as it is in the parafovea; in contrast to the split fovea, the other suggest both hemispheres receive the duplicated information in the fovea (Huber, 1962; Bunt & Minckler, 1977; Bunt, Minckler, & Johanson, 1977; Trauzettel-Klosinski & Reinhard, 1998; Reinhard & Trauzettel-Klosinski, 2003; Gazzaniga, 2000; Miki, Nakajima, Fujita, Takagi, & Abe, 1996). If the word processing in the fovea is qualitatively different from the processing in the parafovea, then it is almost unlikely that the same mechanisms apply to the two different phenomena, one obtained in the fovea (the asymmetric VP curve) and the other in the parafovea (RVF advantage).

The assumptions underlying the cerebral laterality account calls for closer scrutiny. The case for the similarity of the VP curve asymmetry and RVF advantage cannot be established without further examination of at least the two key assumptions. First, same mechanisms underlie the visual field differences within and outside the fovea; there is a processing continuity for words within and outside fovea. Second, the observed VP curve shift is specifically and solely due to the LH hemispheric language dominance.

Brysbaert et al. (1996) addressed the issue of the processing continuity for foveal and parafoveal word processing by examining whether processing asymmetries around fixation fit with the overall performance curve across visual fields. A curve they called the Extended Optimal Viewing Position (EOVP) curve demonstrated a Gaussian distribution fit over recognition performance for words across visual fields (including the stimulus presentations in the fovea and the stimulus presentations in the parafovea). Based on this, they concluded there was a processing continuity of visual word recognition from the foveal to the parafoveal regions. Based on the parameters that fitted to behavioral results, their data fitting approach also revealed some critical features of the VP curve. For example, the left-shifted peak of the distribution suggested a left-to-center optimal viewing position (OVP) as it is seen from empirical human data; moreover, the Gaussian curve showed a larger degree of the VP shifted with longer word suggested an larger VP effect with longer words.

Although their data fitting approach provided important findings regarding to the VP curve, the critical question on the processing continuity between the foveal and the parafoveal regions was not quantatively examined. No direct comparison showed that an estimated curve for word recognition with the processing continuity assumptions provides a better fit to the empirical data than an estimated curve word recognition without such an assumption. In other words, comparisons of the goodness of fit for the fitted Gaussian curves based on two alternative hypotheses - with or without continuity for fovea and parafoveal word processing - was not explicitly examined. A Gaussian distribution fit over recognition performance for words across visual fields may reflect a general trend of visual acuity drop-off from fixation to parafoveal regions. It could be that the same visual acuity function underlies word processing in both the foveal and non-foveal regions; a good fit then may suggest similar word processing across the two regions. However, processing continuity cannot be inferred without a clear indication of level of fitness and statistical tests over the alternative hypotheses.

Martin, Thierry, Démonet, Roberts, and Nazir (2007) examined the processing continuity of foveal and parafoveal word processing using event-related brain potentials (ERPs). They tested two alternative hypotheses regarding foveal processing – namely, whether the information in the fovea is split (projecting to one hemisphere only) or bilateral (projecting the same information to both hemispheres). If word information is projected unilaterally to the contralateral hemisphere for both foveal and the parafoveal stimuli, consistent with a split fovea, then it suggests a continuity of processing from the fovea to the parafovea. By contrast, if words in the fovea are projected bilaterally, then this constitutes a processing discontinuity from the fovea to the parafovea. As an ipsi-contralateral delay of P1 latency has been reliably observed for words flashed parafoveally in a classical Visual Half Field (VHF) procedure (for a review, see Gazzaniga (2000)), this delay is used to infer a unilateral projection. As that is what they also observed for foveally presented words, they concluded that word processing was continuous from fovea to parafovea. Jordan and colleagues, however, questioned their conclusion their since stimuli extended into parafoveal regions (Jordan, Paterson, & Stachurski, 2008; Jordan, Paterson, Kurtev, & Xu, 2010; Jordan, Fuggetta, Paterson, Kurtev, & Xu, 2011). The stimuli used by Martin et al. (2007) subtended 6.65° of visual angle, thereby extending outside foveal vision (up to 1.5 degrees on either side of fixation). The observed unilateral-contralateral P1 latency delay, therefore, could be due to partial information in the parafovea rather than reflecting the nature of foveal processing. Another concern, also raised by Jordan and colleagues (Jordan et al., 2010, 2011), is whether the unilateral projection reflects an anatomical or a functional split in the fovea. In the parafovea, the visual field imply functional divisions associated with the two hemisphere. The argument for a word processing continuity from the fovea to parafovea thus depends on a functional fovea split. As Jordan et al. (2011) did not find an ipsi-contralateral delay for foveally present words in any later components, which they consider as more relevant to word processing than the P1 latency per se, they conclude that word processing is not continuous from fovea to parafovea, contra the cerebral laterality account.

Furthermore, Hunter, Brysbaert, and Knecht (2007) themselves point to factors other than cerebral dominance that could contribute to the observed shifted VP pattern for individuals with atypical language dominance. They repeated Brysbaert (1994) but using functional Transcranial Doppler Sonography (fTCD) and functional Magnetic Resonance Imaging (fMRI) to better screen individuals' language dominance. They replicated the symmetric VP curve for individuals with right hemisphere language dominance, and also observed a positive correlation between the beginning-end asymmetric VP and left hemispheric language laterality [1]. Nonetheless, attentional allocation biases still may contribute to the shift in the VP curve [2].

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[1] "... a direct relationship between hemispheric dominance and word processing in foveal vision, (they concluded) that it is now firmly established that inter-hemispheric communication is needed for normal word reading (p1386, Hunter et al. (2007))"

[2] "... because we did not obtain a contradiction between the laterality index obtained on the basis of the VHF experiments and the laterality index obtained on the basis of the fMRI study for any of the participants we examined (Hunter & Brysbaert, 2008), we feel confident that the results reported below are not a confound of differences in attention allocation across the visual field (p1386, Hunter et al. (2007))"

Two critical assumptions of the cerebral laterality account require further examination: namely, (1) the continuity between foveal and parafoveal word processing and (2) that processing asymmetries in the fovea are due to left hemispheric language dominance.

The key issue centers on the functional hemispheric differences, inferred from visual field differences in the fovea and in the parafovea. Traditionally, the visual field (or/and hemispheric) asymmetries in a behavioral experiment are assessed by comparing performance differences between the responses made by a hand ipsilateral to the stimulated visual field (uncrossed responses) and that made by the hand contralateral to the stimulated visual field (crossed responses). This difference in reaction times, the cross-uncrossed difference (CUD), is taken to reflect the inter-hemispheric transfer time (IHTT), the times it takes to transfer information from one (contralateral) hemisphere to the other (ipsilateral). For instance, presenting the stimulus in the LVF, the CUD, which is based on the across-trial contrasts between right-hand responses (uncrossed responses) and left-hand responses (crossed responses), reveals the time it takes to transfer information from the RH to the LH.

Some reports, however, have raised empirical concerns about estimating the IHTT from the CUD. For example, a negative CUD is often obtained when it is computed from the contralateral hand with respect to the advantaged visual field (Braun, 1992); for example, the left hand response under a condition of the RVF advantage. Moreover, it is not clear exactly what the CUD reflects: whether it reflects the difference in inter-hemispheric transmission of sensory information or motor information (Milner & Lines, 1982). Last but not least, at best estimating IHTT from the CUD is an indirect measure of hemispheric responses via the responding hands across trials.

A (non-neural) behavioral measure will never suffice to answer the question of whether the asymmetric VP effect (in the fovea) and RVF advantage (in the parafovea) are due to the same neural mechanism, as it is indirect measure of brain activity. Estimations of the IHTT from direct brain responses can be derived from the latency differences between early visual evoked potential (VEP) components recorded over the two hemispheres. Contralateral responses following unilateral stimulation are consistently shorter latency than the ipsilateral responses (Andreassi, Okamura, & Stern, 1975; Ledlow, Swanson, & Kinsbourne, 1978; Shagass, Amadeo, & Roemer, 1976). By comparing the ipsi-contralaterl latency delay with the respect to visual field of presentation in both hemispheres, visual field asymmetries (and/or hemispheric asymmetry) can be revealed.

Although the relative speeds of IHTT in the two directions, RH-to-LH versus LH-to-RH, have been associated with the hemispheric differences, there is no consensus as to whether these are functional or anatomical in nature. Faster transfer from the RH to the LH has consistently been found for parafoveal stimuli (Larson & Brown, 1997; Brown, Larson, & Jeeves, 1994; Brown & Jeeves, 1993). Nowicka, Grabowska, and Fersten (1996) observed faster RH-to-LH than LH-to-RH transfer times for a verbal task but the reverse for a nonverbal task, and thus suggested that IHTTs were faster whenever information was transferred from the non-dominant to dominant hemisphere. Ozonoff and Miller (1996), on the other hand, contends that the IHTT differences in the two directions reflect anatomical hemispheric differences. They point out that a relative abundance of fast-conducting myelinated axons in the RH could lead to faster RH-to-LH transfer times. In line with this argument, Barnett, Corballis, and Kirk (2005) found a correlation between increased activation of N160 in RH and faster RH-to-LH transfer times in response to acircular checkerboard, implying factors other than the specialization for language processing can contribute to faster RH-to-LH transfer times.

Given the well-established assessment of visual field differences with the IHTT and the direct measurement the IHTT with the ipsi-contralateral latency delay of the early visual evoked potentials, we propose to investigate the visual field differences for foveal and parafoveal processing using ERPs. Our goal is to use the ipsi-contralateral latency delay of early VEPs to evaluate the similarity of the VP curve asymmetry (reflective of foveal processing) and RVF advantage (reflective of parafoveal processing). We will also measure the ipsi-contralateral amplitude reduction to examine whether the hemispheric differences, if observed, would by accounted by factors other than hemispheric specialization for language. For processing parafoveally lateralized stimuli, we expect a faster RH-to-LH transfer (than LH-to-RH transfer). For processing foveally lateralized stimuli, visual field asymmetries in the fovea, if any, likewise might be reflected in faster RH-to-LH transfer. If these are due to left hemisphere specialization for language, we would expect no differential reduction in VEP amplitudes for transfer between the hemispheres, regardless of direction. However, if this visual field difference in the fovea is not solely due to left hemispheric specialization for language, we would expect a larger amplitude reduction from transfer from RH-to-LH than from LH-to-RH.

6.2.1 The present study

This present study is designed to assess two assumptions critical to the cerebral laterality account: (1) the continuity between foveal and parafoveal processing, and (2) that processing asymmetries in the fovea are solely due to left hemisphere dominance for language. To these ends, we recorded ERPs to stimuli presented in each of the visual fields - either parafoveally (as a proxy for the RVF advantage) or foveally (as a proxy for the VP curve asymmetry). As studies of visual field differences for words have shown that better performance in the RVF could be due to the fact that letters near a word's beginning (which carry more information about the word's identity) are closer to fixation (Jordan et al., 2008, 2010), we used non-word letter strings, also known to show an asymmetric VP curve, instead.

Behaviorally, we expect to replicate Brysbaert (1994) and Brysbaert et al. (1996) with better performance for stimuli – foveal or parafoveal - appearing to the right of fixation. Electrophysiologically, we will characterize visual field differences by inferring the cost of inter-hemispheric transfer time from the ipsi-contralateral latency delay and the amount of information loss from the VEP amplitude reduction. Ipsi-contralateral latency differences are reliably found regardless of visual field of presentation while the effect sizes of both the latency delay and the amplitude reductions vary with the visual field (Brown et al., 1994). Studies have shown consistent findings of faster RH-to-LH transfer time for language processing in the parafovea (Jordan et al., 2011; Nowicka et al., 1996); it can be taken as an index of RVF advantage. If the asymmetric VP curve is a result of same neural mechanism, we expect to see faster RH-to-LH than LH to RH transfer times for the foveally presented stimulus as well. In other words, given the later latency ipsilateral to the stimulus presented visual field, we expect to see the larger ipsi-contralateral latency delay for stimulus presented in the LVF than in the RVF.

As the amplitudes of early sensory components (P1 and N170) generally decrease with stimulus eccentricity (Harter, 1970; Jedynak & Skrandies, 1998), stimuli in the parafovea are likely to elicit smaller amplitudes than those presented foveally. Critically, however, if there is processing continuity between fovea and parafovea, the amplitude drop-off from the fovea to parafovea should not differ with visual field of presentation. By contrast, if one of visual fields shows a more a pronounced drop-off between fovea and parafovea than the other, then the impact of eccentricity is modulated by which visual field the stimulus is presented in. We would take this as evidence against the continuity of processing in the fovea and parafovea.

We will examine the amplitude reduction for transfer from LH to RH and RH to LH to test whether left language dominance is a common neural mechanism for both VP curve asymmetry and RVF advantage. As long as foveal and parafoveal stimuli exhibit the same relationship with the respect to the relative activation levels between the two hemispheres, we maintain the continuity hypothesis. However, if the visual field differences reflected by a faster RH-to-LH in the fovea are not solely due to left hemisphere language specialization, then we should see greater activation in the RH than LH.

In sum, we will examine the assumptions of the cerebral laterality account in the following three ways. First, if there is the RVF advantage for both foveally and nonoveally lateralized stimuli, then there should be faster RTs and greater accuracy for the stimuli in the RVF than in the LVF, whether or not they are foveal. Moreover, the hemispheric differences (due to whatever functional differences) should be indexed by faster RH-to-LH transfer times measured in early VEPs. Second, if there is a processing continuity from the foveal to parafoveal regions, then neither the latency nor amplitude differences between the visual fields should interact with stimulus foveality. Third, if the observed RVF advantage is solely due to LH specialization for language then the amplitude reduction due to the inter-hemispheric transfer from the RH-to-LH and the LH-to-RH should not differ as a function of visual field. Larger RH-to-LH amplitude reductions would implicate other factors, such as a relative abundance of fast-conducting myelinated axons in RH.

Therefore, here are four specific predictions according to the cerebral laterality account: (1) better behavioral performance for the stimuli in the RVF, foveal or not; (2) faster RH-to-LH than LH-to-RH transfer time, whether stimuli are foveal or not; (3) there should be amplitude differences in early VEP components between foveal and parafoveal stimuli, but these differences should not interact with visual field of presentation; (4) if the observed visual field and hemispheric differences are due solely to left hemispheric dominance for language, then the amplitude reduction from one hemisphere to the other will not interact with the direction of transfer.

6.3 Experiment 7: Letter Recognition in a Word

6.4 Method

6.4.1 Participants

Thirty participants from the UCSD social sciences undergraduate subject pool participated in the experiment for either course credit or monetary compensation. Participants had a mean age of 21 (range: 18-26). Thirteen were male, Seventeen female. All of them were right-handed (as assessed by the Edinburgh Inventory (Oldfield, 1971)), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Eleven participants reported having a left-handed parent or sibling.

6.4.2 Stimuli and design

Strings of five lowercase letter k served as stimuli. The possible target letters were c, o, t, or f, and on any given trial one of these replaced one letter of the k-string. For half of the subjects, letter c and t served as target letters in separate sessions (one in each block), and o and f served as distractors in two sessions. For the other half, letters o and f were targets and c and t were distractors. Each character subtended .3° of visual angle at a distance of 95 cm and was defined in a 44 x 36 pixel matrix. Strings were randomly divided into 75 conditions as a function of their visual field of presentation - left visual field, right visual field, spanning across fixation, the relative distance from fixation (0.3 visual degrees with 5 levels of shifts in each visual field), and target letter position within the string.

6.4.3 Experimental Procedure

Participants were tested in two experimental sessions (on two non-successive days within a week) conducted in a soundproof, electrically-shielded chamber. They were seated in a comfortable chair 95 cm in front of a computer monitor and were instructed to perform a yes/no target discrimination task, to which they were to respond by pressing one of two hand-held buttons. Response hand was counterbalanced across participants. Participants were asked to remain still during testing, and to avoid blinking and moving their eyes during stimulus presentation. Every 5 to 7 trials, there were scheduled breaks participants were reminded that they could blink as needed. The session began with a short practice. Participants performed a letter discrimination task (Figure 6.1A). A trial began with a fixation ”+” flashed at the center of the computer screen for 500 msec. Once the fixation disappeared, a non-word letter string was displayed for 20 msec. Figure 6.1B displays a trial sequence. The experiment contained two blocks. In each block, participants pressed a response button to discriminate the target character from two possible distractor characters. Each string was repeated 10 times in each block. Overall, 2250 trials per block were distributed across 6 runs of 375 each in a session (See Table 6.2, Appendix E).

6.4.4 EEG recording

The electroencephalogram (EEG) was recorded from twenty-six tin electrodes arranged geodesically in an Electro-cap (Figure 6.2), each referenced online to the left mastoid. These sites included midline prefrontal (MiPf), left and right medial prefontal (LMPf and RMPf), left and right lateral prefontal (LLPf and RLPf), left and right medial frontal (LMFr and RMFr), left and right mediolateral frontal (LDFr and RDFr), left and right lateral frontal (LLFr and RLFr), midline central (MiCe), left and right medial central (LMCe and RMCe), left and right mediolateral central (LDCe and RDCe), midline parietal (MiPa), left and right mediolateral parietal (LDPa and RDPa), left and right lateral temporal (LLTe and RLTe), midline occipital (MiOc), left and right medial occipital (LMOc and RMOc), and left and right lateral occipital (LLOc and RLOc). Blinks and eye movements were monitored via electrodes placed on the outer canthus and under each eye (referenced to the left mastoid). Electrode impedances were kept below 5 Ω. The EEG was amplified with Grass amplifiers with a band-pass of 0.01 to 100 Hz, continuously digitized at a sampling rate of 250 Hz.

6.4.5 Data Analysis

Trials contaminated by eye movements, excessive muscle activity, drifts, or amplifier blocking were marked offline for elimination from further analysis; on average 6% were lost due to such artifacts. Data with excessive blinks were corrected using a spatial filter algorithm. ERPs were computed for epochs extending from 100 milliseconds before stimulus onset to 920 milliseconds after stimulus onset. Data were normalized to l0uV calibration pulses to rectify differences in gain levels during recording and a digital band-pass filter set from 0.01 to 30 Hz was used on all data to reduce high frequency noise. Data were re-referenced offline to the algebraic sum of left and right mastoids and averaged for each experimental condition, time-locked to the non-word letter string onsets. Averages of artifact-free ERP trials were calculated for each type of target word after subtraction of the 50 millisecond pre-stimulus and post-stimulus baseline.

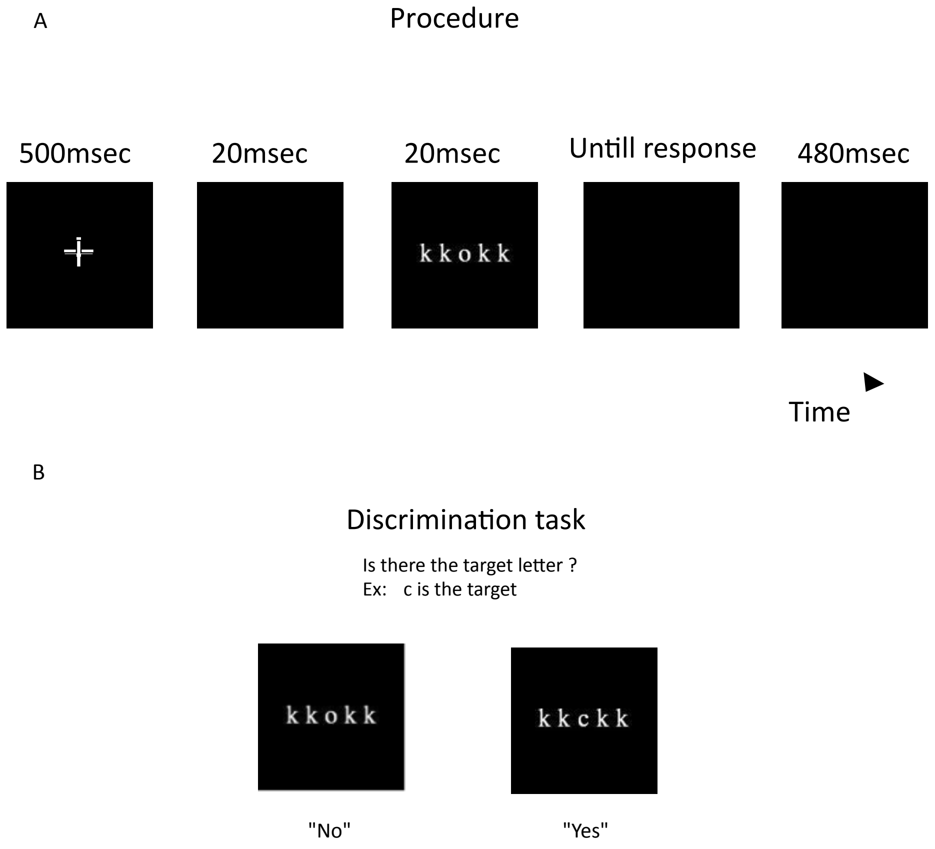

Figure 6.1: Procedure and task in Experiment 7. A: The procedure. B: An example of the letter discrimination task used in Experiment 7. Note that the target letter could be at any one of five letter position within a string.

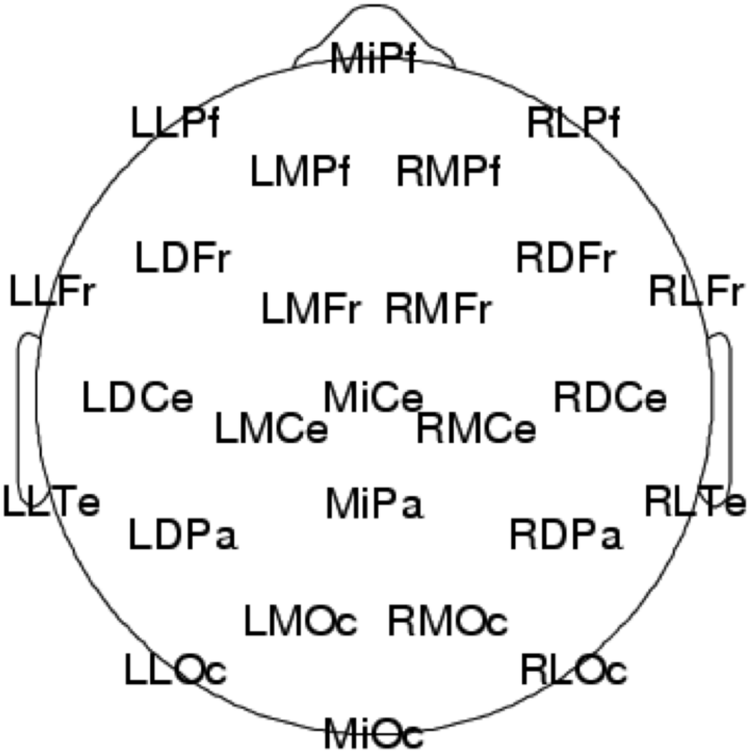

Figure 6.2: Schematic showing the array of the 26 scalp electrodes used in the experiment, arranged in a series of four equally spaced concentric rings.

6.5 Behavior

On average, the accuracy (hit rate) on the target detection task is 70% (74% in fovea and 66% in the parafovea; 69% in the LVF and 71% in the RVF), with average (hit) reaction times of 586 msec (577 msecin fovea and 595 msecin the parafovea; 592 msecin the LVF and 580 msecin the RVF). We performed 3-way partial nested analyses of variances (ANOVAs) on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contra-lateral response to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). Note all measures are within-subjects repeated measures except for IC since response hand was counterbalanced across participants and each participant made Yes-No responses with the corresponding hand throughout the entire experiment (Table 6.1).

Effect of visual field. Performance is significantly better (higher accuracy and faster RTs) for the stimuli presented in the RVF than LVF (Accuracy: $F(1, 28) = 36.71$, $p < 0.0001$; RTs: $F(1, 28) = 11.40$, $p < 0.001$). There is a RVF advantage for both foveally lateralized stimuli (Accuracy: $p < 0.1$ marginal; RTs: $F(1, 28) = 8.01$, $p < 0.05$) and parafoveally lateralized stimuli (Accuracy: $F(1, 28) = 39.71$, $p < 0.0001$; RTs: $F(1, 28) = 7.08$, $p < 0.05$) (Figure 6.3).

Effect of foveality. Performance is significantly better (higher accuracy and faster RTs) for the foveal stimuli than parafoveal stimuli (Accuracy: $F(1, 28) = 20.64$, $p < 0.0001$; RTs: $F(1, 28) = 13.62$, $p < 0.0001$). The better performance for the foveal stimuli is found for both LVF (Accuracy: $F(1, 28) = 10.99$, $p < 0.001$; RTs: $F(1, 28) = 10.99$, $p < 0.001$) and RVF (Accuracy: $F(1, 28) = 27.26$, $p < 0.0001$; RTs: $F(1, 28) = 17.41$, $p<0.001$), but is more pronounced in the RVF than in the LVF

(Accuracy: F (1, 28) = 9.5, $p<0.001$; RTs: $p>0.05$). Moreover, the foveality effect interacted significantly with stimulus eccentricity (Accuracy: F (4, 112) = 4.16, $p < 0.001$; RTs: F (4,112) = 8.78, $p < 0.0001$) for both LVF (Accuracy: F (4, 112) = 2.58, $p < 0.05$; RTs: F (4, 112) = 5.04, $p < 0.0001$) and RVF (Accuracy: F (4, 112) = 5.79, $p < 0.0001$; RTs: F (4, 112) = 5.74, $p < 0.0001$. Follow-up analysis show that the eccentricity effect is significant for the foveal stimuli (Accuracy: F (2, 58) = 4.04, $p < 0.05$; RTs: F (2, 58) = 19.58, $p < 0.0001$) but not for the parafoveal stimuli (Accuracy: $p > 0.1$, RTs: $p > 0.05$).

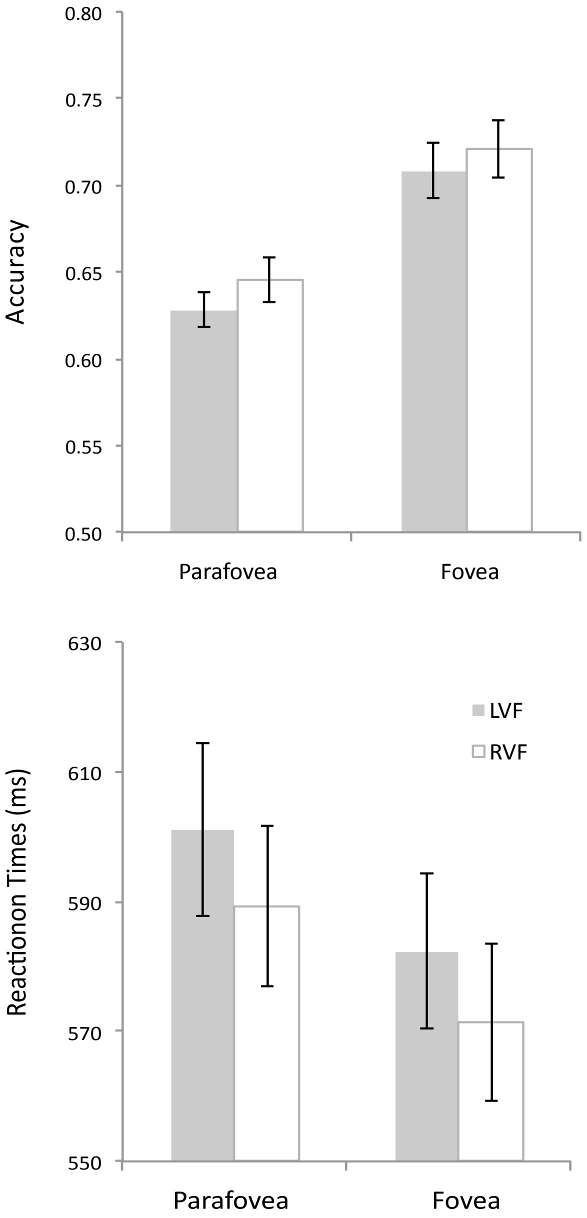

Figure 6.3: The RVF advantage for both foveally lateralized and parafoveally lateralized stimuli. Top panel, recognition accuracy of correct character recognition for foveally and parafoveally lateralized stimuli in each visual field. Bottom panel, reaction times of correct character recognition for foveally and parafoveally lateralized stimuli in each visual field.

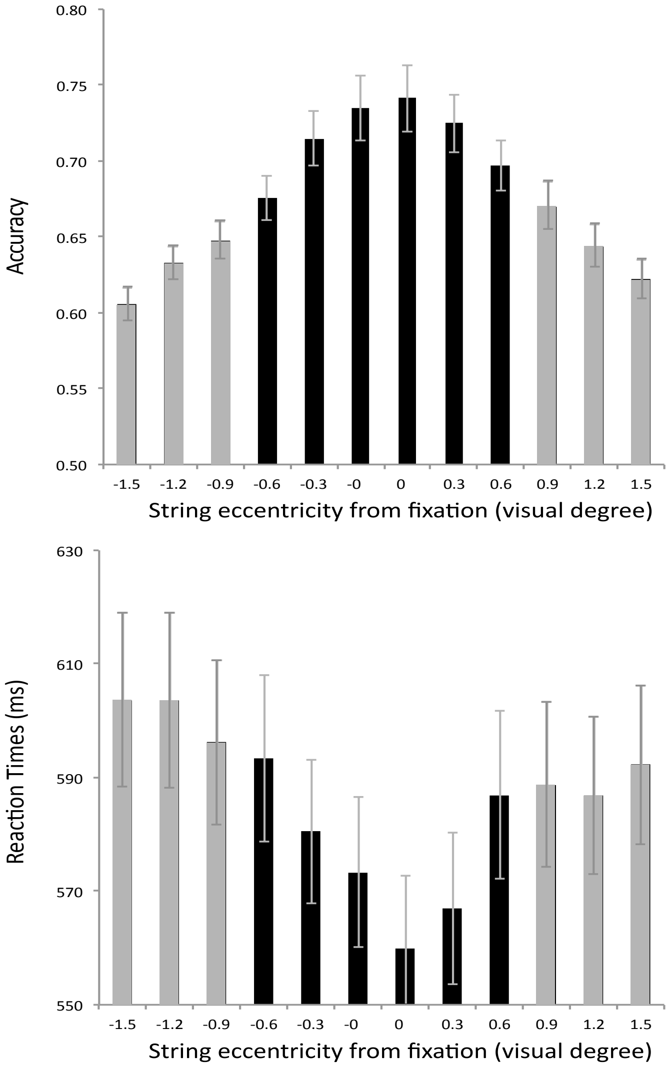

Figure 6.4: Target letter recognition performance as a function of stimulus eccentricity. Negative values represent strings in the LVF, and the positive values represent strings in the RVF. For example, "-0" represents the last letter of a string at fixation with the rest part of the string in the LVF. Performance decreases significantly with the stimulus eccentricity from fixation for the foveally lateralized stimuli (in black) but not for the parafoveally lateralized stimuli (in green). Top panel, recognition accuracy of correct character recognition as a function of string distance from fixation. Bottom panel, reaction times of correct character recognition as a function of string distance from fixation.

6.6 Grand Average ERPs

Grand average ERPs (across all 30 volunteers) to the onset of a non-word letter string from all recording sites in LVF within fovea, RVF within fovea, LVF in the non-fovea, and RVF in the non-fovea are shown in Figure 6.5. Early components in all conditions include, at posterior sites, a positive peaking around 100 msec(P100), a negativity peaking around 190 msec(N190 or N2), at frontal sites, a negativity peaking around 150 msec(N2) and a positivity peaking around 230 msec(P2).

Our analysis focused on the latency and amplitude of two early sensory evoked potentials – occipital P100 and occipital N170 - measured over the occipital electrodes (LLOc and RLOc, Figure 6.6). We performed 3-way partial nested ANOVAs with repeated measures on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contra-lateral electrode to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). All measures are within-subjects repeated measures (Table 6.1).

6.6.1 Peak Latency of the P100 response

The latency of the largest positive peak between 50-150 milliseconds was measured for each condition in each participant and subjected to a 3-way partial nested ANOVAs with repeated measures on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contra-lateral electrode to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). All measures are within-subject repeated measures (Table 6.1).

Ipsi-contralateral latency delay. Mean P100 peak latency is on average 104 msecfrom the lateral occipital electrode contralateral to the stimulus, and 113 msecipsilateral to the stimulus. The ipsi-contralateral delay is significant (F (1, 29) = 74.31, $p < 0.\ 0001$). This ipsi-contralateral latency delay is found for both LVF (F (1, 29) = 72.84, $p<0.0001$), RVF (F (1, 29) = 35.37, $p < 0.0001$), foveally lateralized stimuli (F (1, 29) = 75.34, $p<0.0001$), parafoveally lateralized stimuli (F (1, 29) = 43.93, $p < 0.\ 0001$).

Effects of visual field and foveality. There is neither a significant main effect of visual field ($p > 0.1$) nor a significant main effect of foveality ($p > 0.1$). However, there are 3-way interactions among visual field, foveality, and eccentricity (F (4, 116) = 2.54, $p < 0.05$). The P100 latency delay increases with the stimulus eccentricity only for foveally lateralized stimuli (F (2, 58) = 9.12, $p < 0.\ 05$) but not for parafoveally lateralized stimuli ($p > 0.1$); moreover, the increase of the P100 latency delay with the stimulus eccentricity is found in the RVF (F (4, 112) = 3, $p < 0.05$) but not in the LVF ($p > 0.1$). Figure 6.7 shows grand average ERPs from the lateral occipital site as a function of eccentricity from fixation.

6.6.2 Peak Amplitude of the P100 response

Based on the peak latency analysis, the peak amplitudes were measured within the same time window between 50-150 milliseconds. These measures were subjected to a 3-way partial nested ANOVAs with repeated measures on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contra-lateral electrode to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). All measures are within-subjects repeated measures (Table 6.1).

Ipsi-contralateral amplitude reduction. There is a marginal interaction between foveality and ipsi-contralateral mean P1 peak amplitude (F (1, 29) = 2.92,

$p < 0.1$). Otherwise, none of the following main effects – foveality, visual fields, or distance from fixation, or any other interactions was significant.

6.6.3 Peak Latency of the N190 response

The latency of the largest negative peak between 150-280 milliseconds was measured for each condition in each participant and subjected to 3-way partial nested ANOVAs with repeated measures on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contra-lateral electrode to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). All measures are within-subjects repeated measures (Table 6.1).

Ipsi-contralateral latency delay. The mean N190 peak latency is on average 190 msecat the lateral occipital electrode contralateral to the stimulus, and 209 msecipsilateral to the stimulus. The ipsi-contralateral delay is significant (F (1, 29) = 35.63, $p < 0.\ 0001$) and is evident for both LVF (F (1, 29) = 7.08, $p < 0.05$), RVF (F (1, 29) = 21.03, $p < 0.0001$), foveally lateralized stimuli (F (1, 29) = 71.84, $p < 0.0001$), parafoveally lateralized stimuli (F (1, 29) = 9.88, $p < 0.001$).

Effect of foveality and visual field. There is marginal significantly trend of shorter N190 latencies for foveally lateralized stimuli than for parafoveally lateralized stimuli (F (1,29) = 3.66, $p<0.1$). Moreover, this foveality effect for the N190 latency significantly interacted with the ipsi-contralateral electrode sites (F (4, 116) = 6.41, $p < 0.05$): the contralateral N190 latency for foveal stimuli (184 ms) is significantly shorter that to parafoveal stimuli (194 ms) (Figure 6.8). Critically, the shorter N190 latency for foveally lateralized stimuli (vs parafoveally lateralized stimuli) is modulated by visual field (F (1, 29) = 6.38, $p < 0.05$): it is significant for RVF only (F (1, 29) = 7.42, $p < 0.05$) but not for LVF ($p > 0.1$) (Figure 6.9).

6.6.4 Mean Amplitude Analysis of N190 response

Mean voltage measures were taken in a time window between 150-280 milliseconds to cover the range of N190 peaks across conditions. These measures were subjected to a 3-way partial nested ANOVAs with repeated measures on visual fields (V, two levels: LVF and RVF), ipsi-contralateral (IC, two levels: ipsi and contralateral electrode to the stimulus visual field), and foveality (F, two levels: fovea and parafovea) with eccentricities (EC, three distance levels). All measures are within-subjects repeated measures (Table 6.1).

Ipsi-contralateral amplitude reduction and visual field differences. The amplitude of the occipital N190 is smaller in the hemisphere ipsilateral (than contralateral) to side of stimulus presentation (F (1, 29) = 56.58, $p < 0.0001$). The ipsi-contralateral N190 amplitude reductions are evident for all stimulus condition; however, the effect in the LVF (F (1, 29) = 40.49, $p < 0.0001$) is more pronounced than that in the RVF (F (1, 29) = 6.22, $p < 0.05$). This visual field difference in ipsi-contralateral N190 amplitude reduction (F (1, 29) = 4.79, $p < 0.05$) reflects a larger amplitude reduction from RH-to-LH than LH-to-RH (Figure 6.10); this is significant for the parafoveally lateralized stimuli (F (1, 29) = 5.76, $p<0.05$) and marginal for the foveally lateralized stimuli (F (1, 29) = 3.69, $p < 0.1$) (Figure 6.11).

Effect of foveality and visual field differences. The amplitude of the occipital N190 is larger for the foveal than parafoveal stimuli (F (1, 29) = 53.79, $p < 0.0001$). This foveality effect is driven by the decrease of the N190 amplitude with the stimulus eccentricity for both foveal (F (2, 58) = 42.66, $p < 0.0001$) and parafoveal stimuli (F (2, 58) = 15.65, $p < 0.0001$), albeit more so for the foveal (F (4, 116) = 24.71, $p < 0.0001$) (Figure 6.7). Moreover, although this foveality effect is seen for both visual fields, the difference is larger in the RVF; this is mainly due to larger N190 amplitudes for foveal stimuli in the RVF than in the LVF, while it is not the case for the parafoveally lateralized stimuli (Figure 6.12).

Summary of Main Results

Behaviorally, the RVF advantage is observed for lateralized stimuli both within and outside the fovea. Moreover, whereas performance is generally better for foveal than parafoveal stimuli, this drop is greater in the RVF. The latency of the occipital P100 is longer in the hemisphere ipsilateral (vs contralateral) to the side of stimulus presentation, for all stimulus conditions. For lateralized stimuli within the fovea, the increase of P100 latency with eccentricity is larger in the RVF than LVF; for lateralized stimuli outside the fovea, there is no difference across the visual fields.

The subsequent occipital N190 is both later (in latency) and smaller (in amplitude) ipsilateral (vs contralateral) to the stimulus, whether or not it was within the fovea, on either side of fixation. There were, however, some significant interactions with visual field. First, for stimuli presented in the RVF (but not the LVF), the latency of N190 for lateralized stimuli is significantly longer for stimuli outside the fovea than within. Second, in general N190 is larger for lateralized stimuli within than outside the fovea; moreover, this foveality effect is larger for the RVF than LVF. Third, the ipsi-contralateral N190 amplitude reduction is larger for the stimuli presented in the RVF than the LVF – larger for RH-to-LH transfer (than for LH-to-RH transfer); this directional transfer amplitude reduction is reliable for stimuli outside the fovea and marginal for those lateralized within the fovea.

Table 6.1: Results of regression analysis with behavioral performance, P100, and N170 components. F-values are given.

		Behavioral Performance		P1 component (50 ms- 150 ms)		N170 component (150 ms- 280 ms)	
	Effects	RTs	ACC	P1Lat	P1Amp	N170Lat	N170Amp
All							
	V	**11.40** **	**36.72** ***	0.77	0.32	0.01	2.21
	IC	**5.07** *	0.00	**74.31** ***	0.16	**35.63** ***	**56.58** ***
	F	**17.57** ***	**20.64** ***	2.65	0.04	3.66 ^	**53.79** ***
	V x IC	0.07	0.46	2.45	0.33	0.75	**4.79** *
	F x EC	**8.78** ***	**4.16** **	1.12	1.86	1.21	**33.34** ***
	F x V	0.03	**9.50** **	0.13	2.39	**6.38** *	**24.71** ***
	F x IC	0.07	0.46	0.18	2.92 ^	**6.41** *	0.53
	F x V x EC	0.77	**7.33** ***	**2.54** *	1.08	2.16 ^	0.82
	F x IC x EC	0.63	0.58	0.38	0.26	0.39	**32.72** ***
	F x V x IC	0.71	0.40	0.00	1.65	0.01	0.23
	F x V x IC x EC	**2.88** *	0.40	0.53	0.94	0.10	0.90
LVF							
	IC	0.13	0.20	**72.84** ***	0.45	**7.08** *	**40.49** ***
	F	**10.99** **	**13.62** ***	1.03	1.55	0.76	**37.70** ***
	F x EC	**5.04** ***	**2.58** *	1.17	0.40	0.71	**24.80** ***
	F x IC	0.59	0.21	0.15	**4.37** *	3.36 ^	0.82
	F x IC x EC	1.91	0.45	0.68	0.20	0.90	**13.21** ***
RVF							
	IC	0.87	0.21	**35.37** ***	0.07	**21.03** ***	**6.22** *
	F	**17.41** ***	**27.26** ***	1.75	0.59	**7.42** *	**65.31** ***
	F x EC	**5.74** ***	**5.79** ***	**3.00** *	**3.25** **	0.89	**26.72** ***
	F x IC	0.49	0.61	0.09	0.30	2.33	0.01
	F x IC x EC	1.97	0.37	0.19	1.08	1.54	**17.86** ***
FV							
	V	**8.01** **	4.00 ^	0.92	0.12	2.84	**14.80** ***
	IC	3.18 ^	0.28	**75.34** ***	0.31	**71.84** ***	**51.32** ***
	EC	**19.58** ***	**4.04** *	0.08	0.71	2.53 ^	**42.66** ***
	V x IC	0.63	0.01	2.06	0.01	1.20	3.69 ^
	V x EC	0.91	**9.12** ***	**4.88** *	1.24	0.74	1.18
	IC x EC	0.34	0.21	0.06	0.42	0.13	**43.24** ***
	V x IC x EC	2.84 ^	0.11	0.60	0.23	0.01	1.06
PFV							
	V	**7.08** *	**39.71** ***	0.18	1.60	2.81	0.11
	IC	3.48 ^	0.21	**43.93** ***	1.59	**9.88** **	**48.40** ***
	EC	0.76	4.35 ^	0.08	2.03	0.09	**15.65** ***
	V x IC	0.25	0.55	1.44	1.11	0.42	**5.76** *
	V x EC	0.70	2.87 ^	0.12	0.94	0.05	0.32
	IC x EC	0.81	0.81	0.77	0.12	**4.01** *	**16.43** ***
	V x IC x EC	2.91 ^	0.43	0.48	0.14	0.14	0.59

^ p< 0.1 (marginal) , * p < 0.05, ** p< 0.01, *** p<0.001
V=Visual fields, IC = ipsilateral v.s. contralateral, EC: Eccentricity, F = Foveality v.s. Paraoveality, FV=Fovea, PFV= Parafovea, RTs = Reaction Times, ACC = accuracy (hit rate), P1Lat = P1 peak latency, P1Amp = P1 peak amplitude, N170Lat = N170 peak latency, N170Amp = N170 mean amplitude

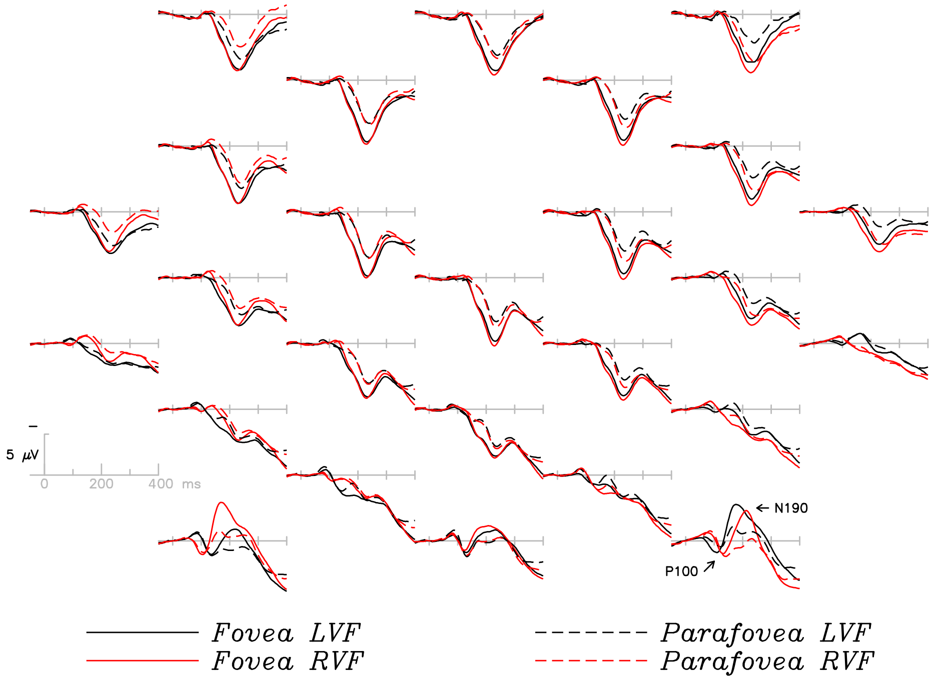

Figure 6.5: Grand average ERP waveforms for the four presentation locations Fovea LVF, Fovea RVF, Parafovea LVF, and Parafovea RVF, at all 26 electrode sites.

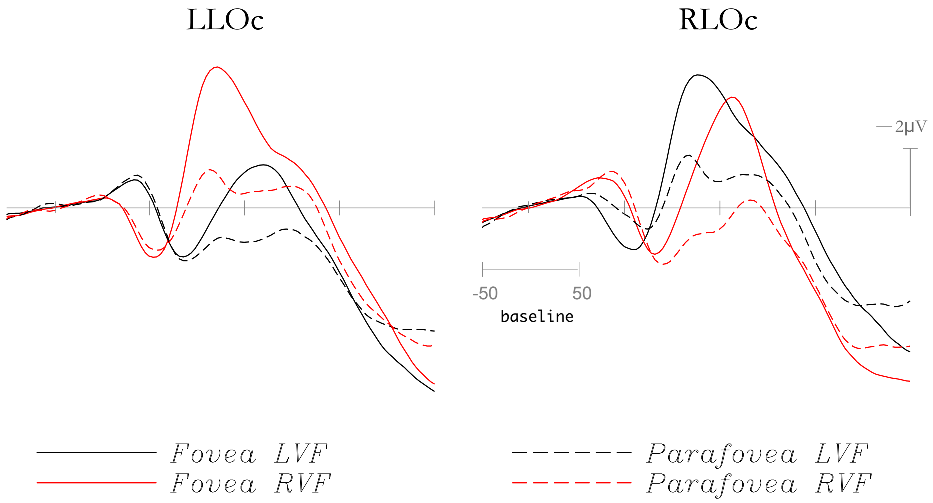

Figure 6.6: Grand average ERP waveforms for the four presentation locations - Fovea LVF, Fovea RVF, Parafovea LVF, and Parafovea RVF, at two lateral occipital sites (LLOc & RLOc).

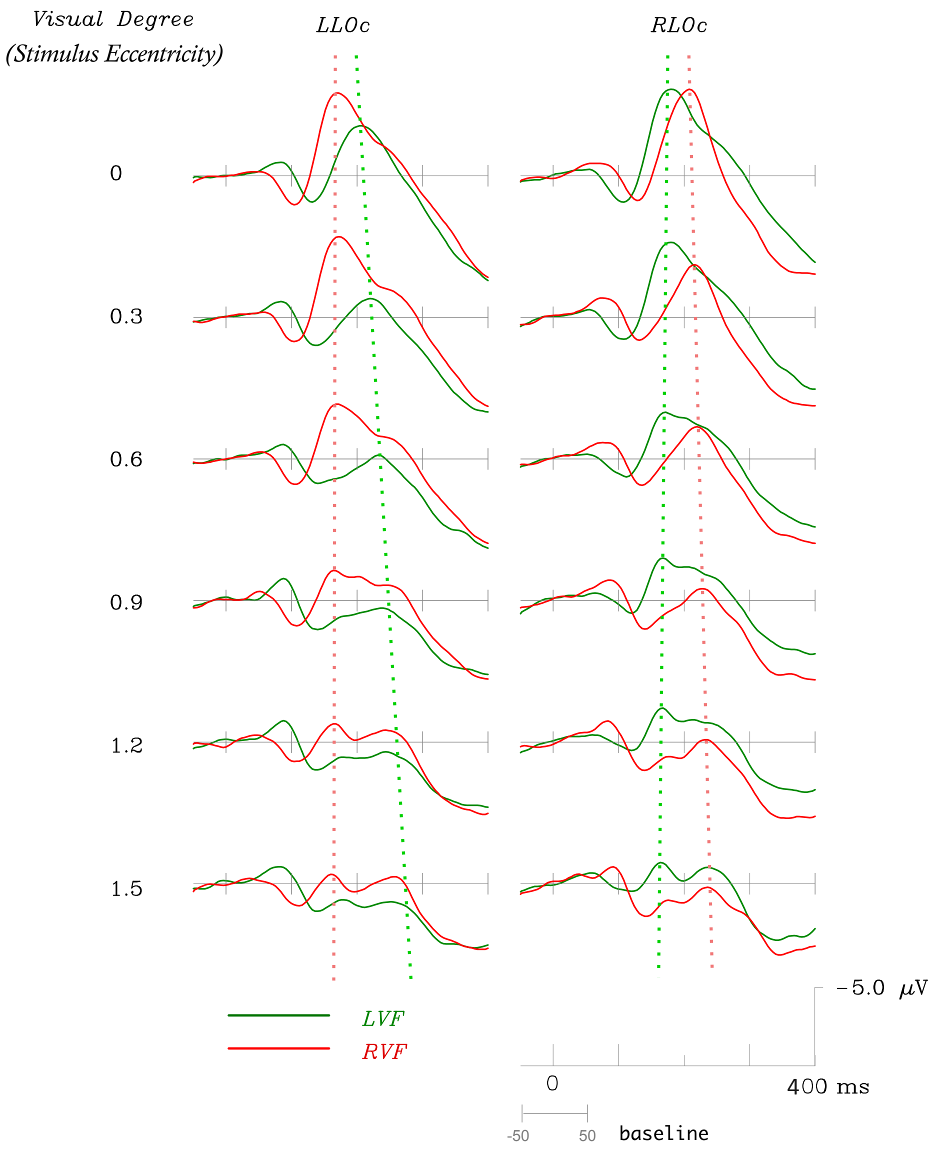

Figure 6.7: Grand average ERP waveforms for various stimulus eccentricities in each visual field, at two lateral occipital sites (LLOc & RLOc). The ipsi-contralateral P100 latency delay increases with stimulus eccentricity in the RVF but not in the LVF. The N190 amplitude decreases with the stimulus eccentricity, more so for the foveally (visual degree ranges from 0 to 0.6) than the parafoveally lateralized stimuli (visual degree ranges from 0.9 to 1.5).

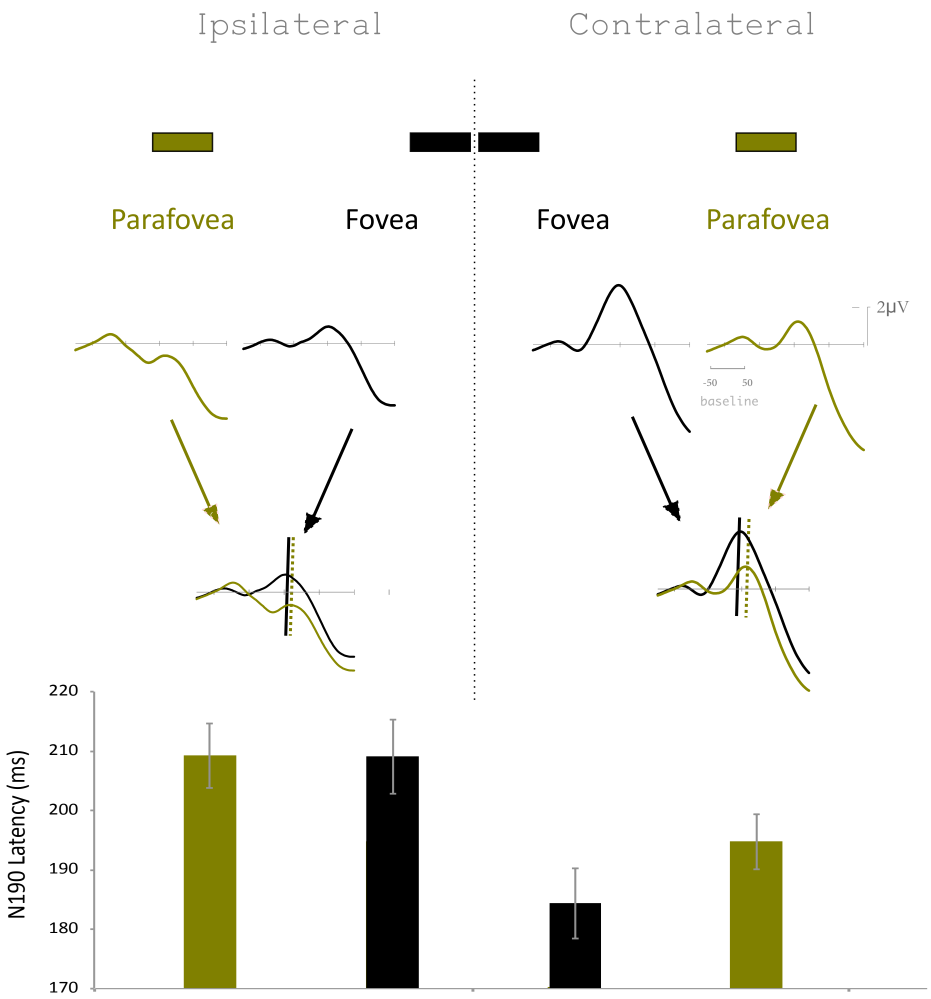

Figure 6.8: Mean N190 latencies for the foveally and parafoveally lateralized stimuli at sites ipsilateral and contralateral to the stimulus visual field. The contralateral N190 latency is shorter for the foveally than for parafoveally lateralized stimuli.

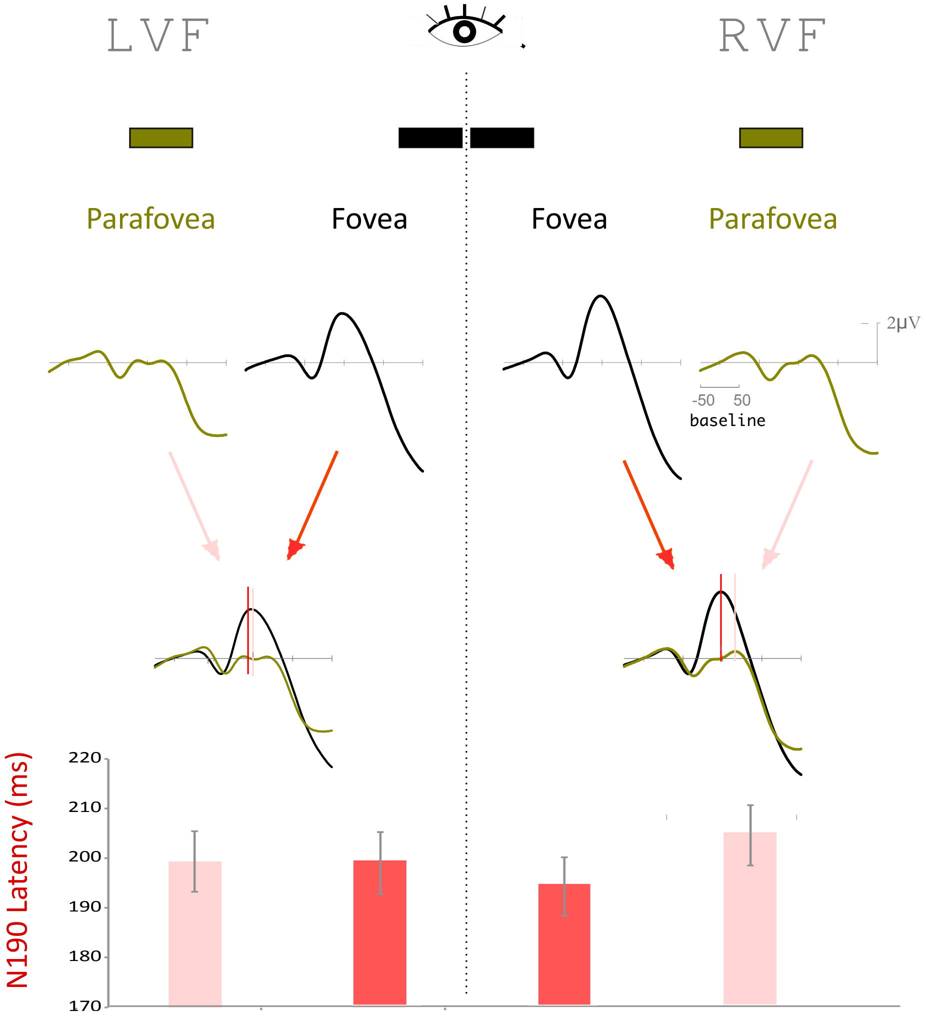

Figure 6.9: Mean N190 latencies for the foveally and parafoveally lateralized stimuli in the RVF and in the LVF. In the RVF, the N190 latency is shorter for the foveally than for the parafoveally lateralized stimuli.

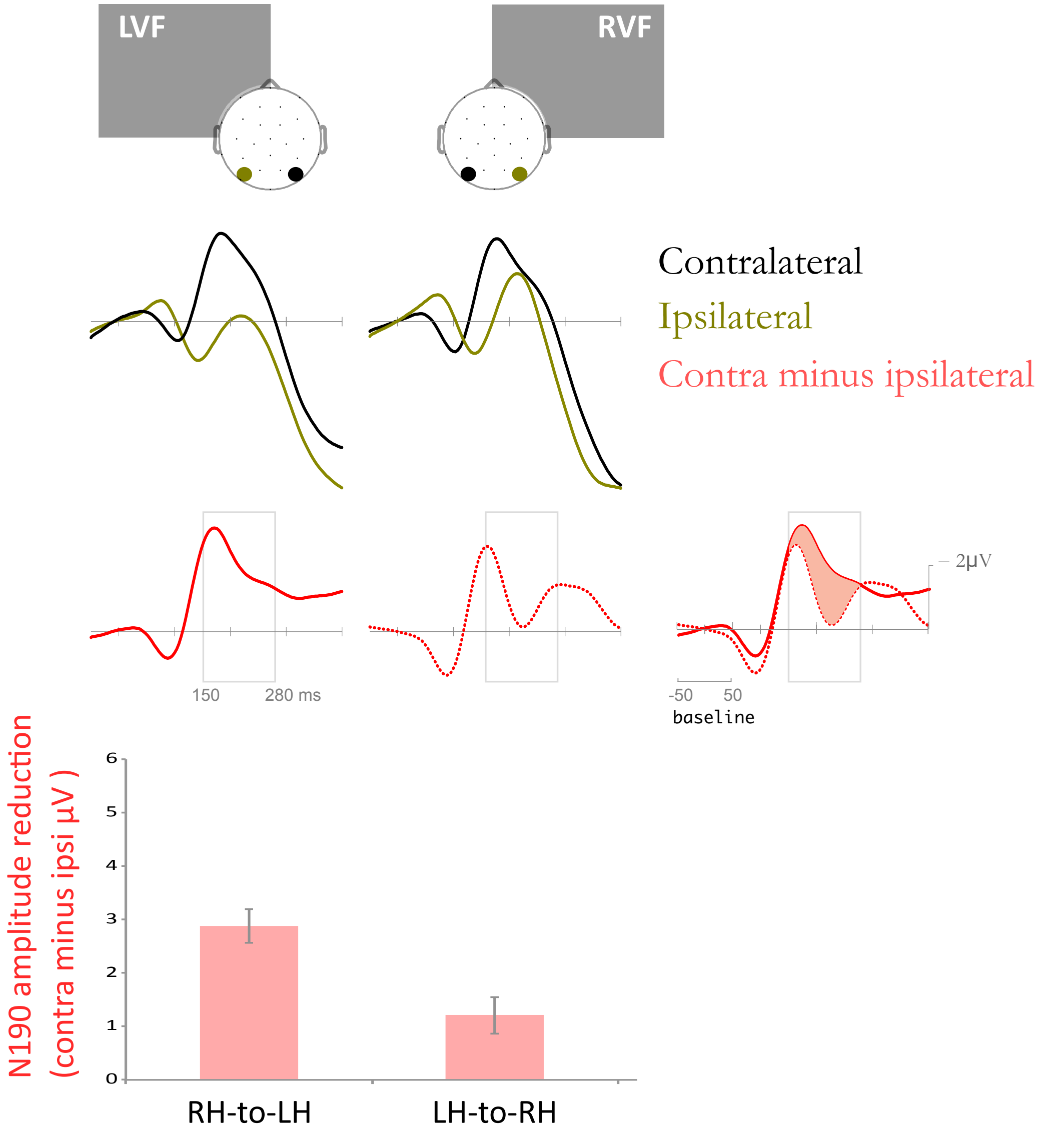

Figure 6.10: Mean N190 amplitude reductions for the inter-hemispheric transfer, the RH-to-LH transfer and the LH-to-RH transfer. The RH-to-LH amplitude reduction is larger than the LH-to-RH amplitude reduction.

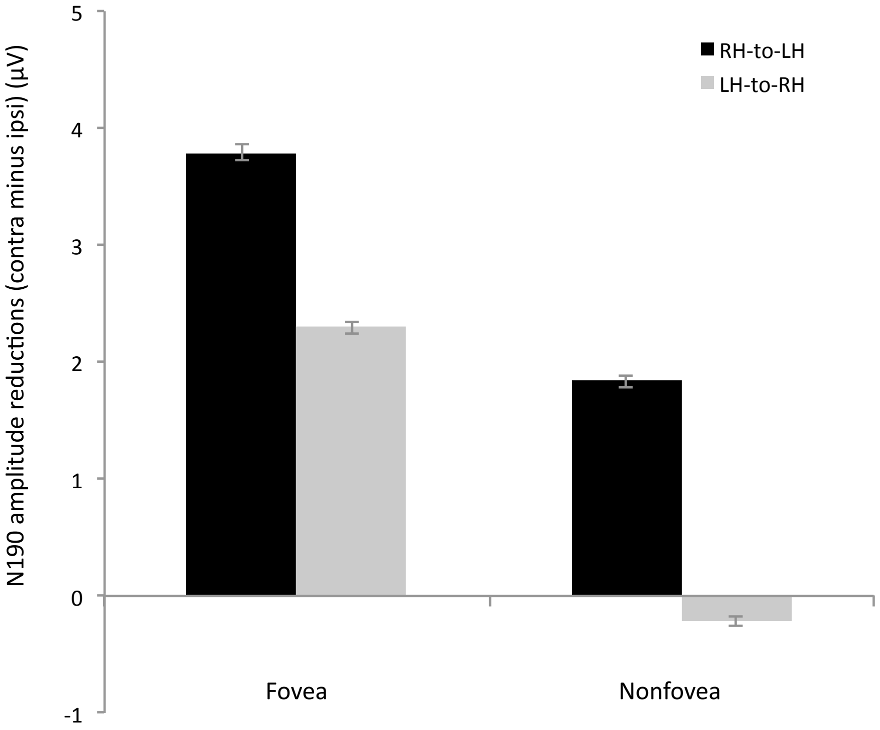

Figure 6.11: Mean N190 amplitude reductions of inter-hemispheric transfer, for the foveally lateralized and parafoveally lateralized stimuli. This asymmetry in amplitude reduction (larger RH-to-LH than LH-to-RH) is significant for the parafoveally lateralized stimuli and marginal for the foveally lateralized stimuli.

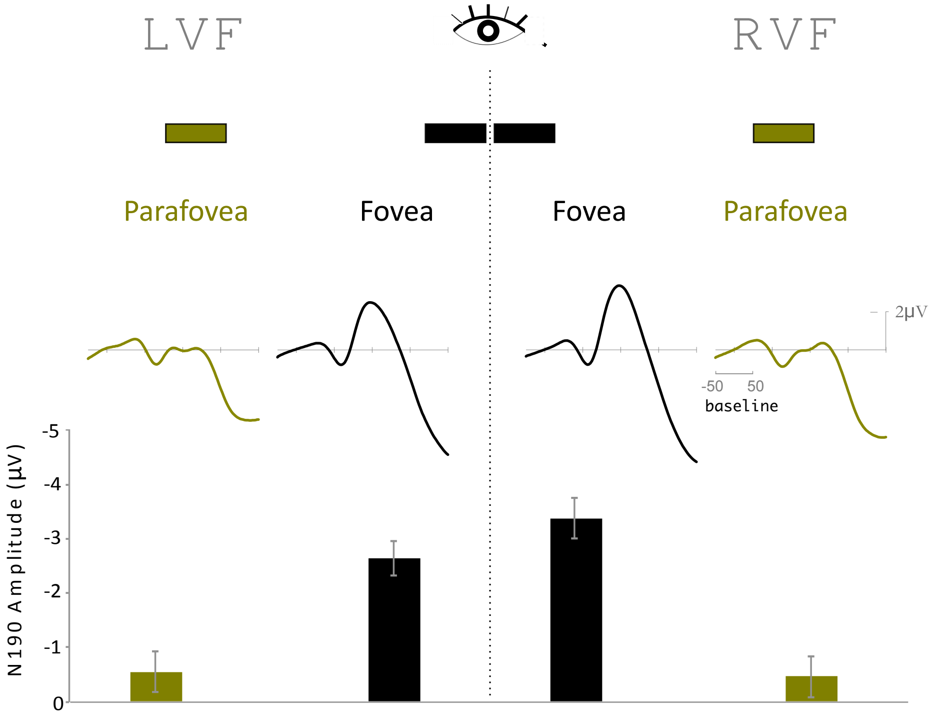

Figure 6.12: Mean N190 amplitude for the foveally and parafoveally lateralized stimuli in the LVF and the RVF. For foveally lateralized stimuli, the N190 amplitude is larger for the stimuli presented in the RVF than LVF. For the parfoveally lateralized stimuli, however, there are no visual field differences in N190 amplitudes.

6.7 Discussion

The present experiment examined two assumptions critical to the cerebral laterality account: (1) whether or not the visual field differences for stimuli within the fovea are attributable to the same mechanisms as those outside the fovea and (2) whether the RVF advantage for stimuli within the fovea is solely due to LH dominance for language. We tested four critical predictions of the cerebral laterality account: (1) RVF advantage would be reflected in better behavioral performance for stimuli in the RVF than LVF; (2) the RVF advantage would also be reflected electrophysiologically in quicker RH-to-LH than LH-to-RH transfer times as measured by the ipsi-contralateral latency delay of the early VEP components (the occipital P1 and the occipital N190). Moreover, the RVF advantage should not differ for lateralized stimuli within or outside the fovea; (3) VEP amplitudes should decrease with eccentricity, leading to a difference within and outside the fovea, regardless of visual field; (4) If the observed visual field and hemispheric differences are solely due to left hemispheric dominance for language, the ipsi-contralateral amplitude reduction in the occipital N190 should not differ with visual field of presentation.

Overall, we find a RVF advantage for these non-word letter strings as predicted. Specifically, we observe a behavioral RVF advantage – greater accuracy and faster reaction times – for lateralized stimuli both within and outside the fovea (See Figure 6.3). This RVF advantage both within and outside the fovea is consistent with reports of an asymmetric VP curve (in the fovea) and RVF advantage (in the parafovea), respectively. Electrophysiological findings an earlier occipital P1 and occipital N190 in the hemisphere contralateral versus ipsilateral to the stimulated visual field, within and outside the fovea. The analysis of ipsi-contralateral latency delay for the occipital

P1 and occipital N190 indicate a faster IHTT for RH-to-LH than LH-to-RH transfer.

According to the cerebral laterality account, visual field differences arise from the cost of transferring information from the language non-dominant to the language dominant hemisphere. Since the transfer is serial – letter-by-letter, the difference between the visual fields depends on the number of letters that need to be transferred to the dominant hemisphere, whether the lateralized stimuli fall within or outside the fovea. Effects associated with foveal versus parafoveal processing, such as the amplitude decrease of the early visual components with stimulus eccentricity, similarly, should not be modulated by visual fields. We would take any interaction between foveality (foveal/parafoveal presentation) and visual field (LVF/RVF presentation) as indicative of a processing discontinuity across the fovea to the periphery, and inconsistent with a single mechanism account.

Our results do seem to suggest a processing discontinuity from the fovea to parafoveal regions of visual space. Although the occipital N190 latency is on average earlier for stimuli lateralized within than outside the fovea, this foveality effect interacts significantly with the visual field of presentation; it is only significant RVF presentation (See Figure 6.9). Likewise, the N190 amplitude differences between foveally and parafoveally lateralized stimuli are larger in the RVF than in the LVF. This pattern of results is hard to reconcile with an account on which the RVF advantage (foveal and parafoveal) is due to LH dominance for language processing.

Alternatively, we suggest that the differences between foveal and parafoveal processing, especially in the RVF may reflect hemispheric differences in coding – namely, fine-coding in the LH and coarse-coding in the RH (Miki et al., 1996). On the coarse-fine coding schema there are relatively larger receptive fields in the RVF than in the LVF (Brown & Jeeves, 1993). Thus, more units of distinct receptive fields respond to stimuli presented in the RVF than in the LVF. This is consistent with our findings that the activation patterns elicited by the RVF stimuli seem more subject to whether they are lateralized in the fovea or in the parafoveal regions, while LVF presented stimuli seem less subjected to the foveality. Moreover, the coarse-fine coding distinction between the LH and RH is widely used to explain biases in spatial attention. Many computational models have successfully implemented the parameters relating to the relative sizes of receptive fields in the LVF and RVF to account for the visual processing asymmetry between the two visual fields (see Monaghan and Shillcock (2004) for a review). Assuming there are attentional gradients with eccentricity, due to the larger (overlapping) receptive fields in the RH, the slope of such an attentional gradient would be less steep in the RH/LVF than in the LH/RVF. On this account, LVF stimuli less affected by being within or outside fovea because the RH is more attentionally engaged than the LH. The mechanisms associated with distinctive coding schema in each hemisphere can account for the visual field differences in the fovea, the visual field differences in the parafovea, as well as the visual field by foveality interaction.

Consistent with this alternative explanation, our analysis of the ipsi-contralateral amplitude reduction of the occipital N190 shows that the amplitude reduction is larger when the stimuli are presented in the LVF; in other words, we see a larger amplitude reduction for information transmission from the RH to the LH. This holds for parafoveally lateralized stimuli, but is marginal for foveally lateralized stimuli. This pattern of result suggests that the observed visual field differences are not solely attributable to LH specialization for language processing.

In conclusion, our findings are not consistent with the predictions of the cerebral laterality account, and thus do not support an explanation of the asymmetric VP effect and the RVF advantage for parafoveal stimuli as both due to left hemispheric specialization for language. The coarse coding hypothesis seems to offer a viable alternative.

6.8 Acknowledgement

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6.9 Appendix E

Table 6.2: The number of trials and target letters for each block in Experiment 7

First half of subjects						
Session 1			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	c	75	10	750	2250
	Distractors	o	75	10	750	
		f	75	10	750	
Block 2	Target letter	t	75	10	750	2250
	Distractors	o	75	10	750	
		f	75	10	750	
Session 2			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	t	75	10	750	2250
	Distractors	o	75	10	750	
		f	75	10	750	
Block 2	Target letter	c	75	10	750	2250
	Distractors	o	75	10	750	
		f	75	10	750	
Second half of subjects						
Session 1			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	o	75	10	750	2250
	Distractors	c	75	10	750	
		t	75	10	750	
Block 2	Target letter	f	75	10	750	2250
	Distractors	c	75	10	750	
		t	75	10	750	
Session 2			# of conditions	# of repetitions	Total # of trials	
Block 1	Target letter	f	75	10	750	2250
	Distractors	c	75	10	750	
		t	75	10	750	
Block 2	Target letter	o	75	10	750	2250
	Distractors	c	75	10	750	
		t	75	10	750	

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Chapter 7

Look here: An event-related brain potential (ERP) investigation of the optimal viewing position (OVP) in word recognition

7.1 Abstract

Since across a number of behavioral experiments we have observed the center-to-left OVP for words only, we used the ERP technique to begin to get a handle on the neural mechanism of this word-specific effect. Specifically we recorded ERPs to words and nonwords presented foveally at two different within-string fixation locations – namely, at the OVP (slightly left of string center) and at the string's center. We expected this fixation manipulation to impact word processing but not nonword processing. Although occipital P100 amplitudes were larger for longer than shorter strings, regardless of lexical status and fixation, only words showed an effect of fixation position. P100 amplitudes over right occipital sites were smaller for words positioned at the OVP than at the word's center; this P100 amplitude difference between fixations is negatively correlated with word length. This pattern of effects leads us to suggest that location normalization for invariance during visual word recognition may

occur around 100 ms.

7.2 Introduction

Skilled readers can quickly recognize words despite large variations in visual format such as spatial position, size, and font. Successful visual word recognition, indeed, relies on the brain's ability to normalize across irrelevant perceptual parameters in order to create an abstract word representation. This abstract word representation, known as "visual word form" (Riesenhuber & Poggio, 1999; Cohen et al., 2000), has been linked to activation in the left fusiform gyrus (Cohen et al., 2000; Price & Devlin, 2003; Cohen et al., 2003; Cohen & Dehaene, 2004). Accordingly, this region has been labeled the Visual Word Form Area or VWFA. Studies using fMRI have monitored activations in the VWFA and surrounding areas in response to written words in the human ventral visual stream (Cohen et al., 2002; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; McCandliss, Cohen, & Dehaene, 2003; Vinckier et al., 2006; Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Szwed, Cohen, Qiao, & Dehaene, 2009; Dehaene et al., 2010; Vinckier et al., 2007; Dehaene, Cohen, Morais, & Kolinsky, 2015; Maurer et al., 2006). From these the consensus view has emerged that skilled readers develop perceptual expertise in creating abstract word representations relying primarily on the integrity of their ventral visual system in which variable format visual information is progressively normalized to an invariant word identity (McCandliss et al., 2003; Vinckier et al., 2007; Dehaene & Cohen, 2011; Dehaene et al., 2015; Maurer et al., 2006; Shaywitz et al., 2002; Rosazza, Cai, Minati, Paulignan, & Nazir, 2009).

The identity of any individual word, however, depends on an exact encoding of its letter order. Faced with words with the same letters in different orders, such as lair, liar, and rail, for example, a system that manages visual word representations in an invariant fashion could not distinguish among these words. A system with location-specific representations likewise would not fare well given that variability in fixations could lead to different representations on the retina for the same word. For instance, there might be more overlap between the visual representations of different words given the same fixation (l*air vs. r*ail; two locations with matching letters) than for the same words at different fixations (l*air vs. lai*r; zero location with matching letters). More generally letter location coding requires an answer to the question of how retinotopic letter locations can be represented in a word-centered letter order so as to maintain the order in the abstract word representation. The brain has solved this problem as the average reader does not find it difficult to identify words that share same letters albeit in different orders nor to identify the same word at different fixations. Information about the specific locations of the letters in a word thus must reside somewhere in the visual system allowing human brains to generate an invariant structural representation of a visual word. We aim to track this progression of a letter string along the ventral stream from perception to the creation of an abstract word representation in VWFA by comparing and contrasting the neural processing of words and nonwords of different lengths at two different fixation locations.

Tracking the location normalization of visual word recognition in the ventral system requires a measure with exquisite temporal resolution in a design that requires letter location coding but does not use an unfamiliar visual format. Recent fMRI studies of visual word recognition have found that skilled readers fail to achieve abstract word processing when words are presented in unfamiliar visual formats (Vinckier et al., 2006; Cohen et al., 2008; Cohen & Dehaene, 2009; Rosazza et al., 2009; Pammer, Hansen, Holliday, & Cornelissen, 2006) then even skilled readers invoke the dorsal processing stream; this has been taken to suggest that invariant representations of visual word forms are computed in the ventral system. To our knowledge, no one has delineated the emergent temporal process of location normalization for words in familiar visual formats presented within the field of perceptual expertise field (i.e., within the fovea).

To this end, we presented variable length letter strings foveally with only a minimal shift in fixation location - the string was centered either at fixation or to a location slightly left-of-string center. To monitor when human brains switch from a location-specific (retinotopic) to location-invariant (word-centered) representation, we used variable length letter strings in which letter combinations led to either real words or nonwords. Effects that vary with number of letters (length) would reflect mechanisms that operate on retinotopic representation, regardless of lexical status (for both words and nonwords). Compared to changes in retinotopic representations due to length, shifts of fixation, on average .225 visual angle in the current study, should have minimal impact for both words and nonwords. However, as the ventral system begins to represent visual information in a word-centered fashion, an impact of fixation would emerge for words (and not for nonwords). Studies have shown that visual word recognition depends on where the eyes initially fixate within a word (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). Various locations within a word provide different amounts of orthographic information as to the word's identity (Clark & O'Regan, 1999). Therefore, a fixation effect that is specific for words, if any, would be taken as a marker of processes associated with location normalization; its time course would provide temporal information about the divergence of word and nonword processing.

Based on the literature, we know that words will show a left-lateralized N170 (around 200 ms) regardless of fixation condition and length (Cohen et al., 2000; Brem et al., 2006; Cai, Lavidor, Brysbaert, Paulignan, & Nazir, 2008; Maurer, Zevin, & McCandliss, 2008; Yoncheva, Blau, Maurer, & McCandliss, 2010). Words displayed in formats within the field of perceptual expertise, as is the case for both fixation conditions in the current design, should be processed as they progress along the ventral visual stream toward an abstract word representation in the VWFA by 200 ms at the latest. The latency of this left-lateralized N170 effect which is taken to reflect the time required to transfer letter information from the right hemisphere to the left VWFA might vary with fixation condition: the latency should be longer for a condition that a word is centered at fixation than a location slightly left-of-word center (Cohen et al., 2000; Cai et al., 2008; Brem et al., 2006). However, we do not expect it to interact with word length given that skilled readers do not show word length effects unless words are displayed in a format outside the field of expertise, in which case processing is subsumed by the dorsal parietal pathway (Vinckier et al., 2006; Rosazza et al., 2009; Pammer et al., 2006). A null interaction effect with word length thus would also assure that our fixation manipulation do not move visual word recognition out of the auspices of the ventral pathway. Given that letter information reaches the VWFA by 200 ms, nonword processing should differentiate from word processing by then. The 200 ms mark, however, cannot be a magic moment (Hauk, Pulvermüller, Ford, Marslen-Wilson, & Davis, 2009) for distinguishing words from nonwords. If so, then we expect to see the emergence of the progressively location-invariant representations specifically for words sometime before 200 ms.

As visual word representation organizes along the visual hierarchy in the ventral system, the switch from a location-specific (retinotopic) to a location-invariant (word-centered) representation, if any, would be manifest in early visual componentry (before N170). The P100 is generated in extrastriate cortex (Martinez et al., 1999; Di Russo, Martínez, Sereno, Pitzalis, & Hillyard, 2002). If it indexes an early process of visual complexity, we expect it to vary with length regardless of lexical status: it should be larger for longer than shorter letter strings – words and nonwords (Hauk et al., 2009; Assadollahi & Pulvermüller, 2003; Hauk et al., 2006, 2009). On the other hand, to the extent that the P100 or any subsequent ERP component indexes a location normalization mechanism, reflecting word-centered instead of retinotopic location information, then whatever the ERP effect, it should vary with fixation but for words only. Moreover, this ERP effect – presumably somewhere between P100 and activation in VWFA around 200 ms – should be modulated by “word” length, given that length is a critical in computing orthographic information (Coltheart, Davelaar, Jonasson, & Besner, 1977).

7.3 Experiment 8: Lexical Decision Task

7.4 Method

7.4.1 Participants

Thirty-eight students from the UCSD social sciences undergraduate subject pool participated the experiment for either a course credit or monetary compensation. Participants had a mean age of 21 (range: 18-32). Fifteen were male, and twenty-three were female. All of them were right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971), native English speakers with normal or corrected-to-normal vision and no history of reading difficulties or neurological/psychiatric disorders. Twelve of volunteers reported having a left-handed parent or sibling.

7.4.2 Material

The stimuli consisted of 150 words and 150 nonwords, with lengths ranging from 4 to 9 letters (25 words/nonwords per length). The frequency distribution over the word stimuli in each word length set was matched to the WebCELEX database (Max Planck Institute for Psycholinguistics, 2001). The letter of each position of a nonword was independently generated randomly from 26 English letters. With a such randomizing procedure, the nonword stimuli consisted of 83 unpronounceable letter strings, 6 pronounceable pseudowords, and 61 partial pronounceable nonwords that consisted of pronounceable syllables in either first half of string (24), second half of strings (35), or somewhere both first and second halves but cannot pronounced as a whole pseudoword (2).

7.4.3 Experimental Procedure

Participants were tested in a single experimental session conducted in a sound-proof, electrically-shielded chamber. They were seated in a comfortable chair around

95 cm in front of a computer monitor and were instructed to perform a yes/no lexical decision task, to which they were to respond by pressing one of two hand-held buttons. Assignment of response hand was balanced across subjects. A trial began with a fixation "+" flashed at the center of the computer screen for 500 msec. Once the fixation disappeared, the stimulus displayed for 20 ms either centered at fixation or at the OVP. The string was followed by a blank screen for as long as the volunteer made their responses. After the response had been making, another blank screen followed for 480ms, after which the next trial appeared automatically. Participants were asked to not blink or moving their eyes during stimuli presentation. Every five to seven trials, there were scheduled pauses and texts were shown on the screen to remind participants that they could make some eye blinks if they needed. The session began with a short practice run; a separate set of words and nonwords were used in the practice from the real experimental sessions. Stimuli were presented four blocks of ninety words. Participants were given a short break after each block.

7.4.4 EEG recording

The electroencephalogram (EEG) was recorded from twenty-six tin electrodes arranged geodesically in an electrocap (Figure 7.1), each referenced online to the left mastoid. These sites included midline prefrontal (MiPf), left and right medial preffontal (LMPf and RMPf), left and right lateral preffontal (LLPf and RLPf), left and right medial frontal (LMFr and RMFr), left and right mediolateral frontal (LDFr and RDFr), left and right lateral frontal (LLFr and RLFr), midline central (MiCe), left and right medial central (LMCe and RMCe), left and right mediolateral central (LDCe and RDCe), midline parietal (MiPa), left and right mediolateral parietal (LDPa and RDPa), left and right lateral temporal (LLTe and RLTe), midline occipital (MiOc), left and right medial occipital (LMOc and RMOc), and left and right lateral occipital (LLOc and RLOc). Blinks and eye movements were monitored via electrodes placed on the outer canthus and under each eye (referenced to the left mastoid). Electrode impedances were kept below 5 Ω. The EEG was amplified with Grass amplifiers with a band-pass of 0.01 to 100 Hz, continuously digitized at a sampling rate of 250 Hz.

7.4.5 Data Analysis

Trials contaminated by eye movements, excessive muscle activity, drifts, or amplifier blocking were marked for elimination offline before further analysis; on average 6% were lost due to such artifacts. ERPs were computed for epochs extending from 100 milliseconds before stimulus onset to 920 milliseconds after stimulus onset. Data were normalized to l0uV calibration pulses to rectify differences in gain levels during recording and a digital band-pass filter set from 0.01 to 30 Hz was used on all data to reduce high frequency noise. Data were referenced offline to the algebraic sum of left and right mastoids and averaged for each experimental condition, time-locked to the word and nonword onsets. Averages of artifact-free ERP trials were calculated for each type of stimuli (various lengths of words/nonwords centered to fixation/OVP) after subtraction of the 50 ms pre-stimulus and 50 ms post-stimulus baseline.

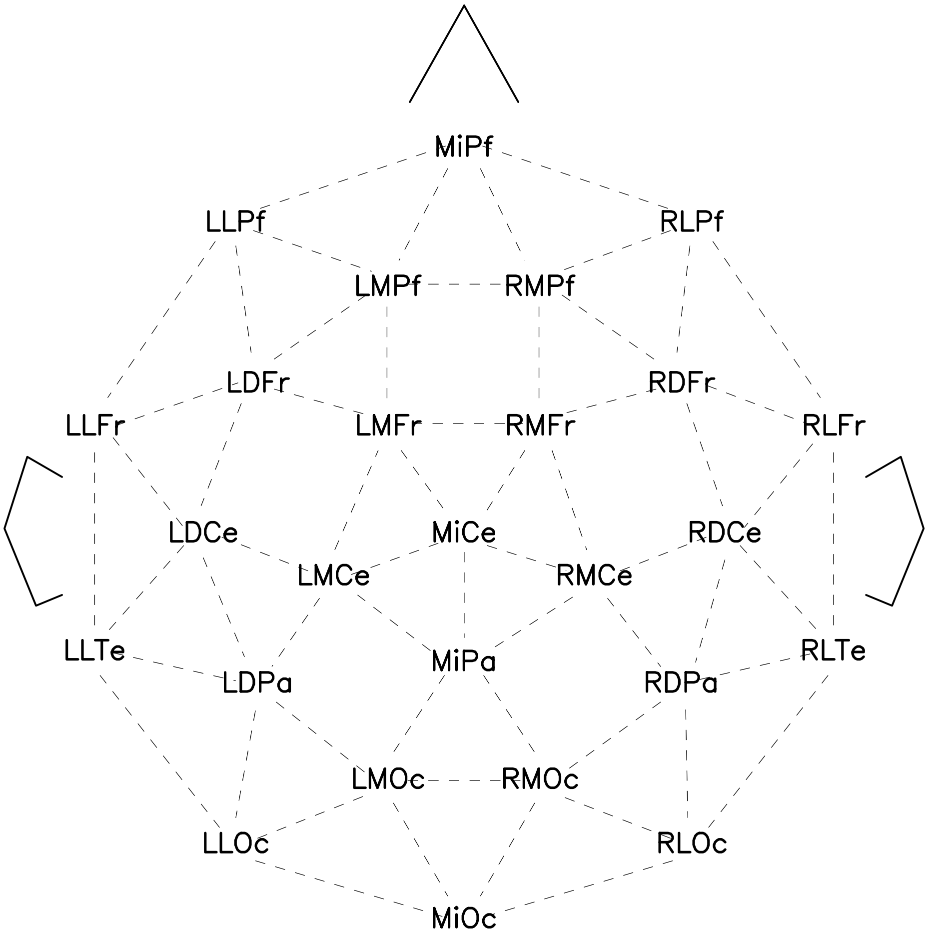


Figure 7.1: Schematic showing the array of 26 scalp electrodes used in the experiment

7.5 Behavior

One average, participants correctly responded to 96% (range 87% 100%) of the items with an average reaction time of 564 ms (range 500 ms - 717 ms) in the lexical decision task. Reaction times falling outside ± 2.5 standard deviations were considered outliers and excluded from further analysis. First, we performed repeated measures linear regressions (Lorch & Myers, 1990) on reaction times to examine the lexicality effect. Second, effects of string length and fixation location for words and nonwords were examined in separate regressions. Third, the differences of fixation by length interaction for words and nonwords were examined. Finally, accuracy was also analyzed to examine these effects using generalized linear models with a logit link function (Jaeger, 2008; Bates & DebRoy, 2004; Pinheiro, Bates, DebRoy, Sarkar, et al., 2007; Breslow & Clayton, 1993) given that accuracy was binomial (yes and no response on the lexical decision task). Random effects were intercept of subjects; likelihood ratio tests were used to obtained p values.

Effects of lexicality. On average, lexical decision accuracy for words (95%) was slightly lower than for nonwords (97%); this difference was statistically significant (F (1, 37) = 18.40, p<0.0001) (Figure 7.2A). There was no significant main effect of lexicality for reaction times (p> 0.5).

Effects of length. For words, lexical decision accuracy significantly decreased with word length (F (1,37) = 4.29, p < 0.005) while reaction times significantly increased with word length (F (1, 37) = 50.23, p < 0.0001). In other words, the longer a word, the less accurate and slower was the decision that it was a word. Reaction times increased around 19 ms for every two additional letters in a word. For nonwords, by contrast there was a positive correlation between lexical decision accuracy and string length ($r = 0.76$, $F(1, 37) = 3.00$, $p < 0.005$), indicating greater accuracy for rejecting longer than shorter nonwords (Figure 7.2B and 7.2C). There was no significant correlation between nonword string length and lexical decision times ($p > 0.1$).

Effects of fixation. For both words and nonwords, there were no main effects of fixation location on reaction times or accuracy. By contrast, the fixation effect on reaction times was positively correlated with word length ($r = 0.43$, $F(1, 37) = 8.36$, $p < 0.005$) (Figure 7.2D). This fixation by word length interaction on reaction times was found for words only ($p > 0.4$).

Summary of Main Behavioral Results

Words and nonwords show the opposite pattern of the main effect of length on lexical decision accuracy: length effects with lerecognition probability: longer words were slightly more difficult to classify as words than shorter words while longer nonwords were easier to reject than shorter nonwords. Lexical decision times increased with string length for words only. Although there was no main effect of fixation location, the reaction time difference between the two fixations was positively correlated with word length.

7.6 ERPs

Effects of lexicality. Based on the literature, we expected robust left-lateralized effects around 200 ms in response to words compared to nonwords. To determine the time course and distribution of this lexicality effect, we performed a two-tailed, repeated measures t-test with the amplitude voltage differences between words and nonwords at every time point for the entire epoch (from 0 ms to 920 ms) over the left electrodes vs right electrodes (11 pairs). The “tmax” permutation procedure (Blair & Karniski, 1993; Hemmelmann et al., 2004) was used to correct for multiple comparisons over time points and electrodes using a family-wise alpha level of 0.05. To estimate the tmax distribution of all possible permutations, this permutation test and all other such tests in this study used 5,000 permutations, which is five times more than the minimum recommend by Manly (1997) for the alpha level of 0.05.

The differences in ERP amplitudes between words and nonwords from recording sites over the left and right hemispheres diverge around 200 ms (Figure 7.3). The statistical analyses show that the left-lateralized lexicality effect starts at 232 ms after stimulus onset and lasts until 356 ms at lateral occipital sites ($0.0002 < p < 0.0223$) (Figure 7.3 and Figure 7.4). This effect is consistent with previous reports of left-lateralized occipital activations around 200 ms, which have been taken to reflect the engagement of visual word form (VWFA) in the occipital-temporal region. Left-lateralized activations were also found over the prefrontal sites (244 ms- 356 ms; $0 < p < 0.035$), frontal sites (240 ms - 356 ms; $0 < p < 0.0414$), and central sites (264 ms - 280 ms; $0.0354 < p < 0.0462$) (Figure 7.3). Increased activations in response to words compared to nonwords over both left frontal and left occipital sites are consistent with previous findings that the processing in the VWFA is co-lateralized with language areas to the left hemisphere, which is language dominant in the majority of population (Rosazza et al., 2009; Cai et al., 2008; Pinel & Dehaene, 2010).

Effects of length. The earliest known length effect is on the occipital P1 component with an onset around 60 ms and a peak around 100 ms after stimulus onset (Manly, 1997; Assadollahi & Pulvermüller, 2003; Hauk et al., 2006). Our data too show a P1 onset at 60 ms with a peak around 112 ms where long words and nonwords elicited a larger P1 compared to short words and short nonwords. Two separate permutation procedures were conducted, one for words and another for nonwords, to test for mean amplitude differences between short (4- 5- 6- letters) and long (7- 8- 9- letters) strings for the occipital P1 (60 -140 ms) at the two occipital electrodes (LLOc and RLOc). Both words and nonwords showed a significant main effect of length at the right occipital site (Words: $t(37) = 2.42$, $p < 0.05$; Nonwords: $t(37) = 3.26$, $p < 0.01$). See Figure 7.5.

Effects of fixation. We conducted a moving window analysis over all the recording sites to examine effects of fixation location. Separate analyses were conducted for words and nonwords on mean amplitudes differences between fixation locations, for 50 ms moving window sliding every time point from stimulus onset up to 250 ms post stimulus onset. The permutation procedure was applied to correct for multiple comparisons across electrodes. The earliest window showing a significant effect of fixation for words is 60 -110 ms; the effect continues through 90 -140 ms and is observed at the right lateral occipital site (RLOc) only ($t\ (37) = 3.18$, $p < 0.05$). P1 amplitudes are larger for words positioned at the word's center compared to a left-to-center (OVP) position. By contrast, nonwords do not show any effect of fixation in any time window at any electrode. See Figure 7.5.

A subsequent analysis was conducted to examine this early effect of fixation of the P1 to words, specifically to investigate its relationship to word length. We performed a repeated measures least squares regression analysis (Lorch & Myers, 1990) on the 26 scalp channels in the earliest window where the main effect of fixation position was significant (60 - 110 ms). This revealed a significant negative correlation between word length and mean amplitude (more positive ERPs, i.e. larger P1 differences, with shorter words) at the right lateral occipital site ($r = -0.39$, $p < 0.05$). The same procedure applied to nonwords revealed no significant correlations at any electrode site (RLOc: $r = -0.09$, $p > 0.5$). See Figure 7.6.

Summary of Main ERPs Results

Occipital N170 amplitudes in response to words compared to nonwords were larger over left than right scalp recording sites. The occipital N170 showed no main effect of word length or fixation location. In an earlier time window, occipital P100 amplitudes were larger for longer than shorter strings, regardless of lexical status or fixation location. There was a reliable effect of fixation location at the right occipital site for words only: P100 amplitudes were smaller for words positioned at the left-to-word center (i.e., OVP) than positioned at the word's center. This P100 amplitude difference between the two fixation locations was correlated with word length.

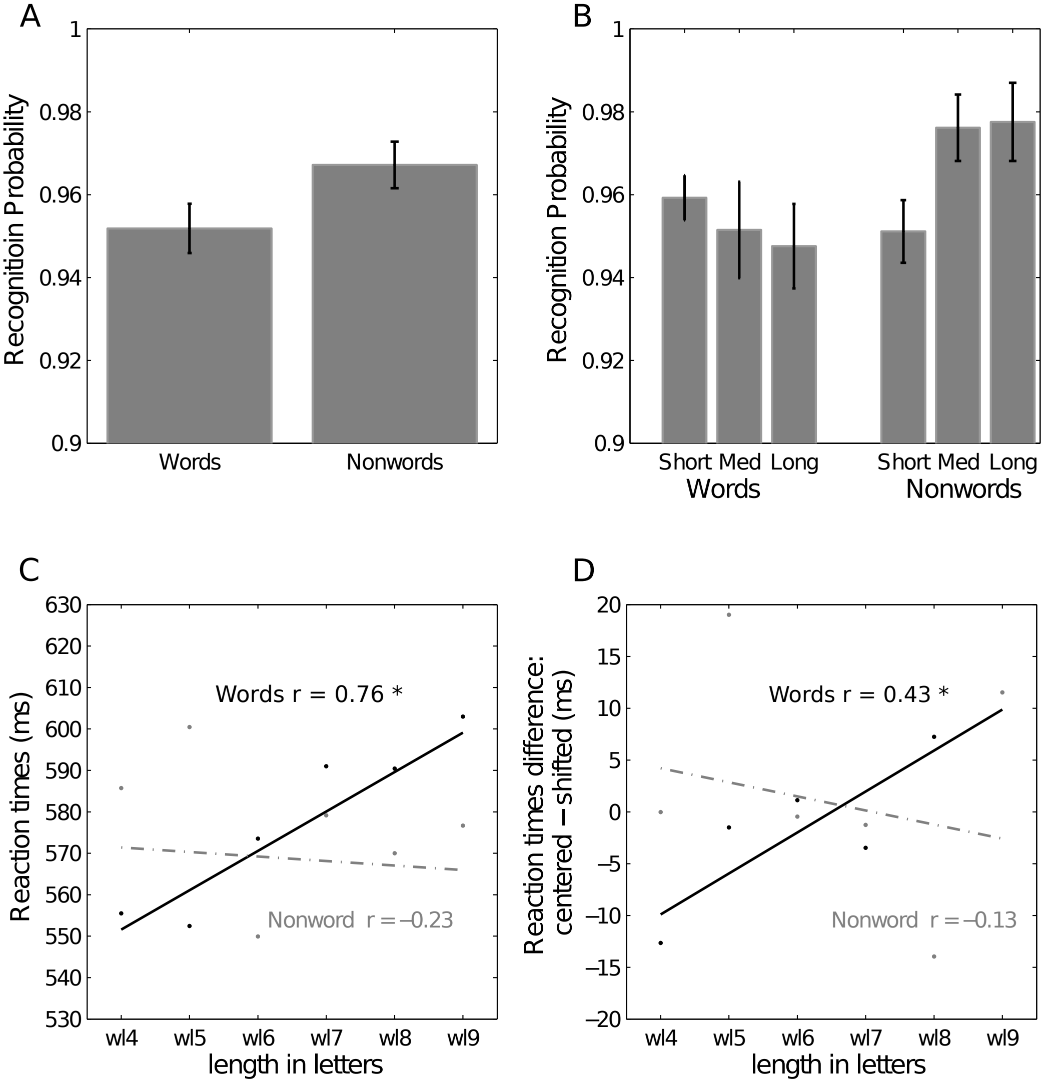


Figure 7.2: Behavioral results in Experiment 8. (A) Accuracy for words and nonwords. (B) Accuracy decreased with length for words but increased for nonwords. (C) For words, lexical decision times were positively correlated with word length. (D) For words, reaction times between conditions of fixation were positively correlated with word length.

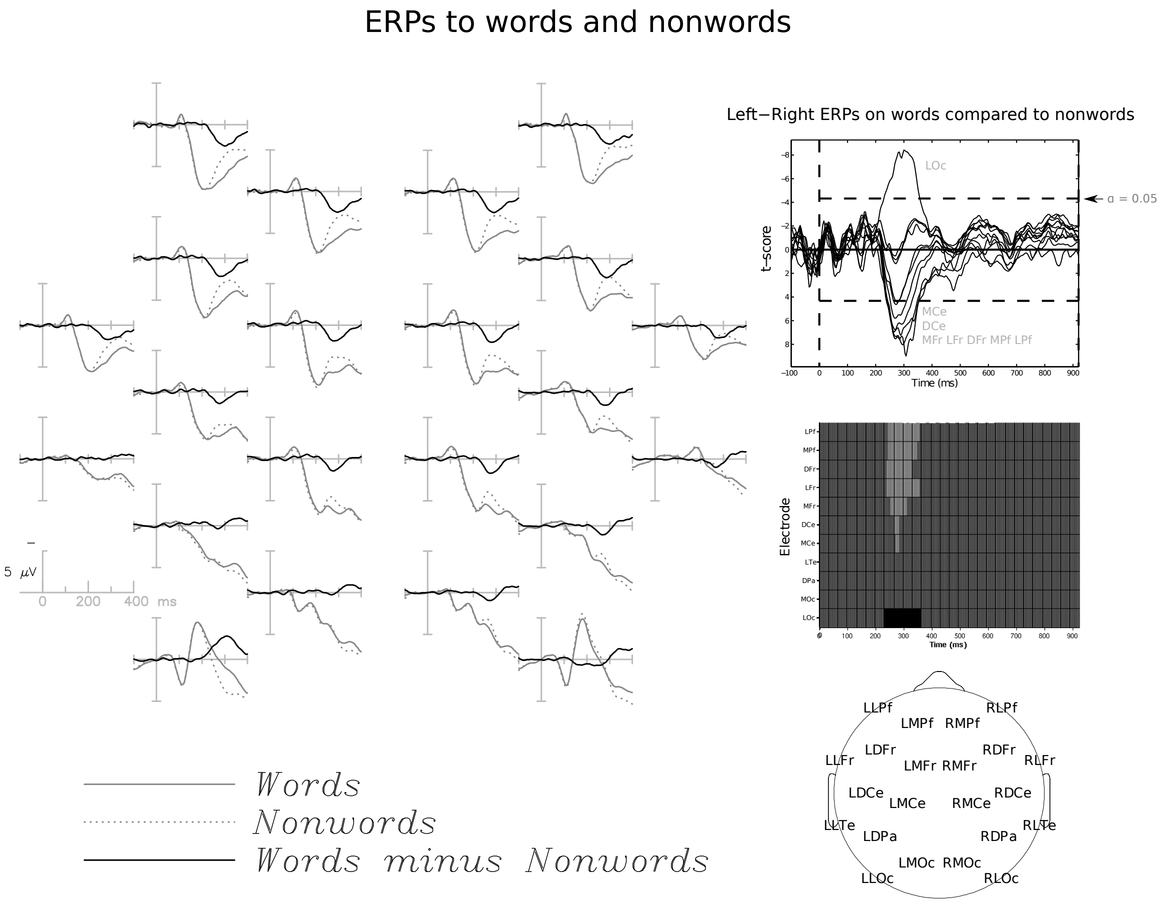
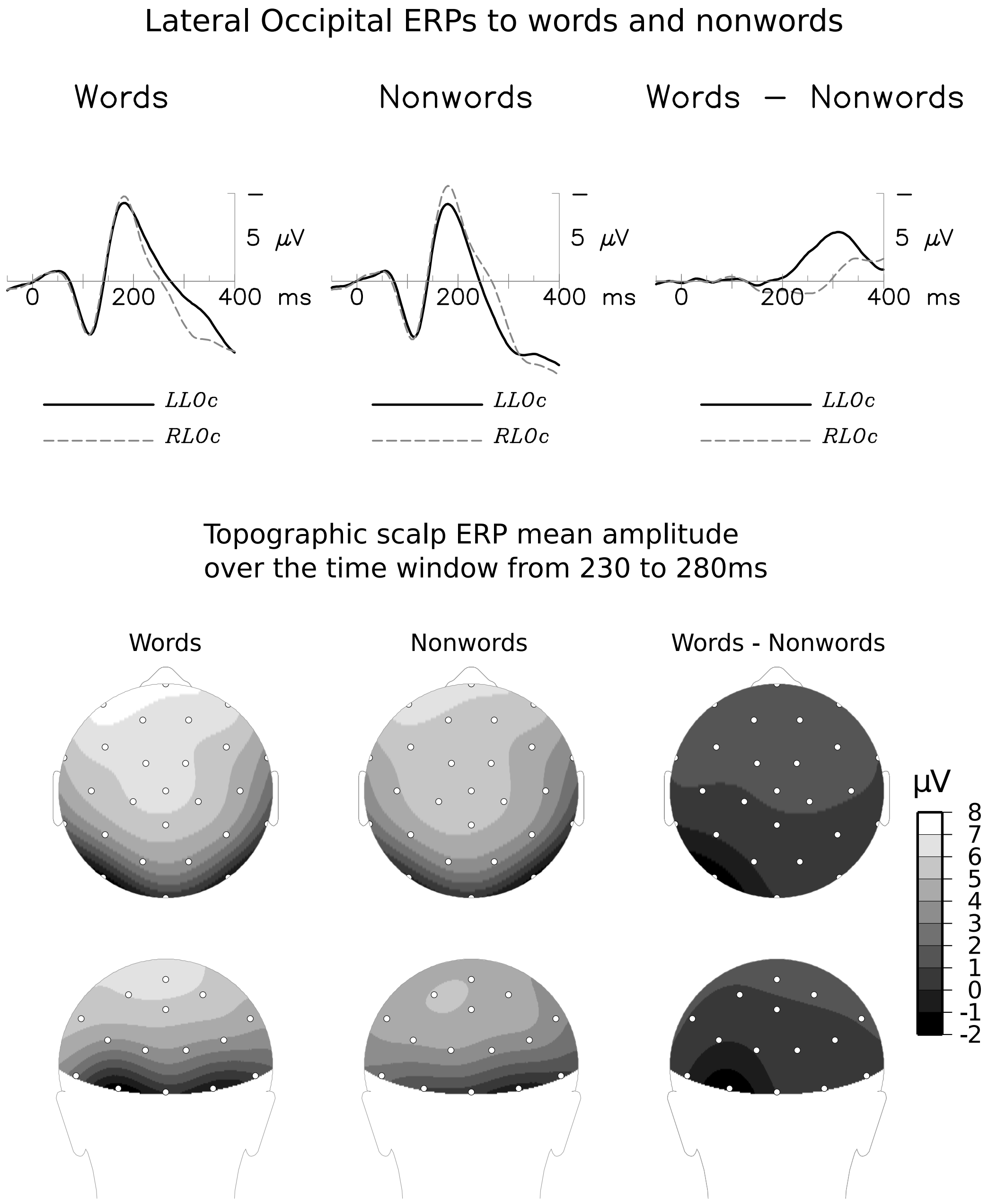


Figure 7.3: ERPs to words and nonwords. Illustrative ERPs at the lateral occipital sites to words, nonwords, and their difference ERPs are shown in the upper panel. Left lateralized activations to words compared to nonwords around 200 ms are shown in topographic scalp maps of the mean ERP amplitudes over the time window from 230 ms to 280 ms in the lower panel.



Lateral Occipital ERPs to words and nonwords

Topographic scalp ERP mean amplitude over the time window from 230 to 280ms

Figure 7.4: Lateral occipital ERPs to words and nonwords. Illustrative ERPs at the lateral occipital sites to words, nonwords, and their difference waves are shown in the upper panel. Left lateralized activations to words compared to nonwords around 200 ms are shown with topographic scalp ERP mean amplitude over the time window from 230 ms to 280 ms in the lower panel.

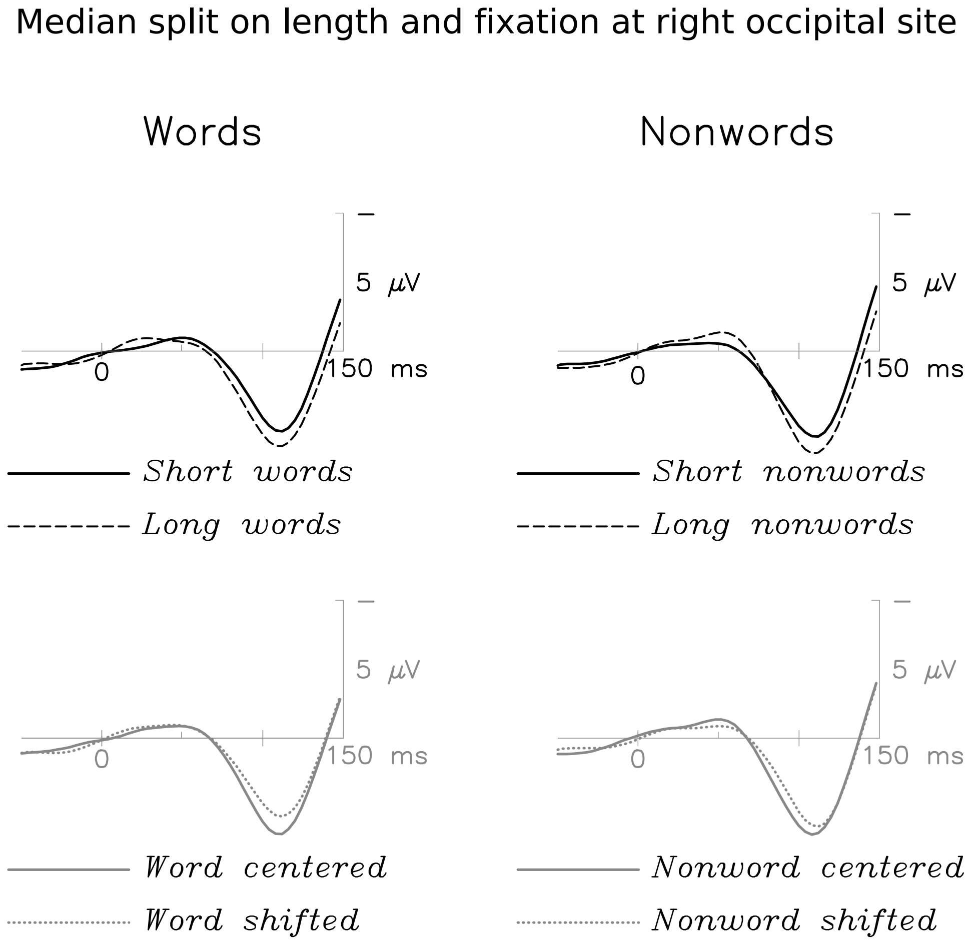


Figure 7.5: ERPs at the right occipital site after median split on stimulus length and fixation. Negative amplitudes are plotted up. Both longer words and nonwords elicit greater positivity between 70-140 ms post-stimuli onset (P100) than their shorter counterparts. In the lower panel, ERPs at the right occipital site for the two fixation conditions. Words centered at fixation elicited larger positivity than those not centered at fixation.

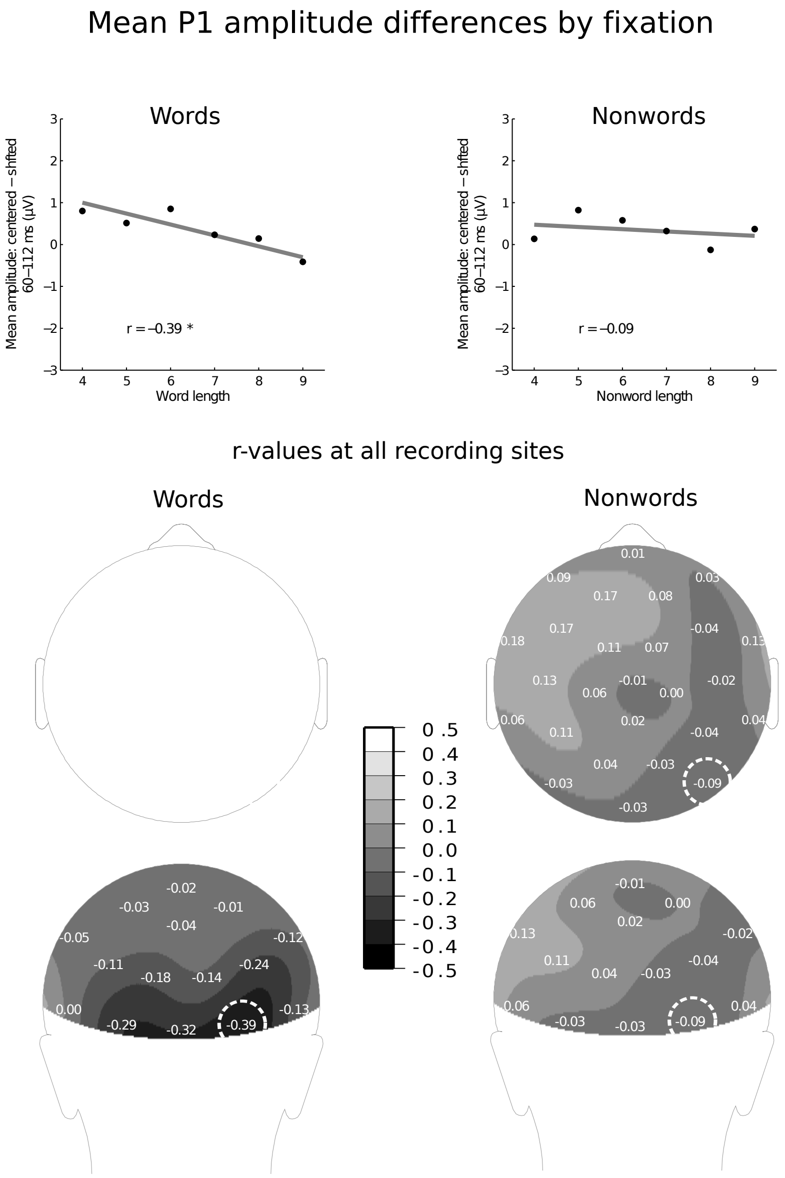


Figure 7.6: P100 mean amplitude differences by fixation for words and nonwords by string length at the right occipital electrode. P1 mean amplitudes were inversely correlated with word length. Scatter diagrams show inverse relations between word length and P100 amplitude at the right occipital site for words only ($r = -0.39$, $p < 0.05$). Best-fitting regression lines are plotted. Although the correlation for nonwords is not significant, the scatter diagram and the regression line are provided for a comparison. The r-values for all 26 electrode sites plotted on an idealized head with top and back views. Darker shading indicates larger negative correlations. The dotted circle demarcates the right occipital electrode.

7.7 Discussion

In the present study, we use ERPs to track the process of location normalization during visual word recognition. To monitor when human brains transition from a location-specific (retinotopic) to a location-invariant (word-centered) representation during visual word recognition, we compare the neural processing of words and nonwords of different lengths at two slightly different fixation locations. Despite the fact that the retinotopic representation of a string changes with different foveal fixations, a word presumably progressively moves toward an abstract representation in the ventral system as long as the stimuli appear within the field of perceptual expertise. We hypothesize that effects that vary with number of letters for words and nonwords reflect mechanisms that operate on retinotopic representations. In contrast, as word-centered representation emerges in the ventral system, then whatever ERP effect, it would reflect an impact of fixation location for words only. We would take this point of divergence between words and nonwords with fixation location as a potential marker of processes involved in location normalization.

P100 amplitudes over the right occipital site to letter strings vary with number of letters in the string, regardless of lexical status: the longer a word or a nonword, the larger the right occipital P100 amplitudes. This early occipital P100 sensitivity to string length is in line with previous reports of word length effects in this latency range; it suggests this early length effect reflects physical properties of the eliciting stimuli (Hauk et al., 2006). Its presence for both words and nonwords, regardless of fixation, is consistent with a location-specific process that operates on a retinotopic representation.

There is, however, a reliable effect of fixation on the P1 at the right occipital site but for words only: P100 amplitudes are smaller for a fixation at the left-to-word center (OVP) than a fixation at the word's center. If this fixation effect indexes a location-specific processes (due, for example, to a slight difference in the number of letters in each visual field when fixating slightly left of center), it should be present for nonwords as well. However, it is not.

We tentatively propose that this P100 amplitude modulation to words as a function of fixation location implicates processes associated with the divergence of word and nonword processing. One finding in the present study – the negative correlation between the P100 fixation effect and word length - suggests that this process might be a location normalization process for words. The P100 amplitude difference as a function of fixation location decreases as word length increases. This P100 amplitude difference thus may reflect the effort it takes to normalize the locations between two fixations. For shorter words, the proportion of the length of the shift for the center to left fixation relative to the word's total length is larger than for longer words. Although this also holds for nonwords, they do not show a correlation between P100 amplitude and length as a function of fixation location. A mechanism that operates solely on retinotopic representations cannot explain this interaction between string length and fixation location for words but not for nonwords.

Taken together the early effects on the occipital P100 - the main effect of string length regardless of lexical status, the main effect of fixation location for words, and the correlation with word length as a function of fixation location - allow us to delineate a process of location normalization for words. For the first time, we show early visual word processing (before 200ms) for location normalization in a familiar visual format. It has been suggested that invariant representations of visual word forms are computed in the ventral system and allow skilled readers to quickly recognize written words. In contrast, processing of words in unfamiliar formats has been found to engage the dorsal stream. Our findings, therefore, offer data on when and perhaps on how the human brain arrives at invariant word representations by location normalization during visual word recognition.

Despite the many reliable reports of length effects on occipital P100, it has proven difficult to determine if the early length effect around 100 ms is due solely to physical stimulus properties such as visual complexity and the number of letters, or is associated with lexical variables. Our results – which show different effects on words and nonwords - suggest that a single visual perceptual mechanism cannot fully explain these P100 amplitude modulations. On the one hand, the P100 amplitudes increase with the number of letters regardless of lexical status, consistent with variation in physical stimulus properties. On the other hand, P100 amplitudes decrease with a slight shift of fixation but for words only and this cannot be explained by physical stimulus properties which do not differ for words and nonwords.

Taking its topographic distribution at face value, the right lateralized word length effect on P100 amplitudes is consistent with the behavioral findings showing that word length effects are larger for words presented in the left visual field, which presumably reflects visual word processing in the right hemisphere via a relatively serial processing mode (Ellis, 2004). This suggests that early activation differences may be associated with lexical information processing differences between the two hemispheres.

The topographic distribution of early right occipital activation found in the present study is also consistent with what Dufau, Grainger, and Holcomb (2008) reports for repetition priming with words. They describe an attenuation of the right occipital N/P100 amplitude for words paired with semantically related primes compared to unrelated primes. This effect, however, diminished with a slight shift in spatial location between the prime and target words. By contrast, the N250 was unaffected by a shift in prime locations. They tentatively argue that the sensitivity of the N/P150 to location supports a recent proposal by Tydgat and Grainger (2009) that letter detectors, the specialized processors to orthographic processing, have relatively narrow receptive fields. According to Dufau et al. (2008), the location-specific N/P150 may reflect the narrowed receptive fields of letter detectors. They conclude that the differential location sensitivities of the N/P150 and N250 suggest a transition from location-specific to location-invariant orthographic coding in visual word recognition between 150ms to 250ms. Our results suggest that the transition from location-specific (retinotopic) to location-invariant (word-centered) representation may occur even earlier as reflected in the P100 fixation effect.

Our results also speak to proposals concerning visual field differences for word processing; especially those that postulate that left hemispheric specialization for language can explain such an early effect. For example, words appearing in the fovea show the optimal viewing position (OVP) effect – recognition superiority for a fixation at a position slightly left of the word's center and demonstrate a right visual field superiority. Our P100 amplitude attenuation to words fixated at the OVP indicates an influence of fixation earlier than 200ms, and is consistent with an early visual perceptual mechanism and/or a role for cerebral laterality. As we observe this P1 attenuation for words only, we conclude that the OVP effect cannot be explained by a single visual perceptual mechanism that does not take language specialization into account.

In conclusion, the present study demonstrates a functional mark associated with the location normalization in visual word recognition occurring around 100 ms. While occipital P100 amplitudes reflect the physical properties of stimuli, this amplitude modulations also reflect the sensitivity to a location shift of fixation for words. Critically, this sensitivity to location shift is modulated by word length. We argue that these word only effects imply a transition from location-specific to location-invariant representation during the location normalization in visual word processing.

7.8 Acknowledgement

Chapter 7, in part, is currently being prepared for submission for publication of the material. Wen-Hsuan Chan; Thomas P. Urbach; Marta Kutas. The dissertation author was the primary investigator and author of this material.

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Chapter 8

Conclusion

My dissertation examines the viewing position (VP) curve (J. O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984) asymmetries in detail across a series of behavioral and electrophysiological studies with the broad aim of better understanding visual word recognition. In particular, my studies were designed to assess the three major accounts of viewing position asymmetries - informativeness, cerebral laterality, and perceptual learning. Critically, these three major accounts are not mutually exclusive; rather they emphasize different aspects of visual word recognition - the structure of words, the anatomical and functional organization of human brains, interactions between word characteristics and brains as modified by experience, respectively (Brysbaert, 1994; Brysbaert, Vitu, & Schroyens, 1996; Nazir, O'Regan, & Jacobs, 1991; Aghababian & Nazir, 2000; Clark & O'Regan, 1999; J. O'Regan et al., 1984; J. K. O'Regan, 1989). While there seems to be supportive data for each of these accounts, it has proven difficult to tease apart their individual contributions and to isolate the responsible mechanisms (Brysbaert & Nazir, 2005). Given the nature of the mechanisms proposed to explain VP curve asymmetries - the structure of word and its distribution of informativeness regarding word identity, left hemisphere specialization for word processing, and asymmetric tuning of visual acuity during acquisition of reading skills – research to date using word stimuli has been riddled with confounds.

I eliminated some of these confounds by using a variety of stimuli - some of which were not words. This choice in turn led me to utilize a target discrimination task in a viewing position paradigm that could readily be performed with a whole host of character strings including but not limited to letters or words. With these stimulus materials – ranging from words to strings constituted of progressively less letter-like features, I was able to investigate the three main viewing position curve effects - its U-shape, the beginning vs end asymmetry, and the left-to-center optimal viewing position (OVP) asymmetry, and thereby better assess the three main accounts of the two asymmetric effects. My experimental approach is aimed to determine the extent to which any of the viewing position effects are specific to words, without assuming that words are special linguistic objects distinct from visual objects more generally. Across six experiments, I systematically manipulated the stimulus characteristics ranging from non-word letter strings (Experiment 1), strings of characters with letter-like features (Experiment 2), strings of characters that were not distinguished by letter-like features, which we called ring sequences (Experiment 3), same three stimulus types in a within-subject design (Experiment 4), to the more traditional stimuli – pseudowords (Experiment 6) and words (Experiment 5). The target discrimination task that I adopted to investigate these various non-word stimulus types in a viewing position paradigm had the added benefit of allowing me to measure recognition performance with greater granularity – namely, at a character level rather than merely at the word level as is typical of the literature on the viewing position curve based on word stimuli.

These stimulus and task choices allowed me to ask the following specific questions with respect to the nature of the viewing position effects and the main theoretical accounts. In the following, I examine each of questions in turn in brief and in the latter section, I will consider the implications of the data for an understanding of viewing position effects in particular and visual word recognition more generally.

(1) Are the beginning vs end VP asymmetry and/or the left-to-center OVP asymmetry word-specific? If not, how does the nature of the stimulus characteristics, specifically non-word strings consisting of characters with letter-like features affect the viewing position curve and its effects? If so, can we find an electrophysiological index of this word specific effect?

I found that the beginning vs end VP asymmetry is not specific to words; strings of characters with letter-like features also exhibit this asymmetry (Experiments 1-4 & Experiments 6-7). By contrast, the left-to-center OVP asymmetry seems to be word specific (Experiment 5 & Experiment 8).

(2) To what extent can each of the three major theoretical accounts explain the viewing position curve and effects for any given stimulus and/or the pattern of VP asymmetries across all stimulus types?

The presence of beginning vs end VP asymmetry across all types of stimulus types (ring sequences, letter-like features, letter strings, words) is consistent with the perceptual learning account (Experiments 1-4 & Experiments 6-7). However, it cannot explain the absence of the left to center OVP asymmetry for strings of non-word letter or letter-like features. By contrast, the presence of the left-to-center OVP asymmetry for words only is consistent with both the informativeness and cerebral laterality accounts, neither of which explains the beginning vs end VP asymmetry for non-word stimulus (Experiment 5 & Experiment 8).

(3) With respect to the perceptual learning account, is recognition consistently better in the right visual field than in the left visual field for stimulus strings constituted of characters with letter-like features?

In line with the perceptual learning account, recognition is consistently better in the right visual field than in the left visual field for strings consisting of letter-like features (Experiments 1-4 Experiment 6).

(4) Also, with respect to the perceptual learning account, are there any other factors – e.g., visual crowding – besides visual acuity that drive the viewing position curve? If so, how does it influence the viewing position curve for different stimulus string types? And, to what extent can these effects be accommodated by existing theoretical accounts?

We find that character recognition is influenced by visual crowding regardless of stimulus type and that the crowding is asymmetric for strings of letters and letter-like features (Experiments 1-6 in Chapter 4 & Chapter 5). None of extant accounts in their current form considers visual crowding at all. While the perceptual learning account could potentially incorporate visual crowding as a consequence of perceptual tuning during reading skill acquisition, neither the informativeness nor cerebral laterality can straightforwardly address visual crowding effects in the viewing position curve.

(5) With respect to the cerebral laterality account, do electrophys-

iological indices of visual field processing asymmetries in the parafovea extend to processing in the fovea?

There seems to be a processing continuity between the parafovea and fovea as reflected in the pattern of electrical brain activity. However, the nature of this processing continuity interacts with visual field and recording site (Experiment 7).

Next, I discuss the implications of my data for an understanding of viewing position effects in particular and visual word recognition more generally. For my entire set of stimulus string types ranging from words, pseudowords, letter strings of the letter k, strings of characters with letter-like features, to strings of incomplete ring sequences, all the viewing position curves are characterized by a U-shape. All viewing position curves but those for ring sequences exhibit better performance at string beginning than string end. And, only the VP curve to words is characterized by a left to center optimal viewing position (See Table 8.1).

All three theoretical accounts agree that the general U-shape of the VP curve reflects the drop off in visual acuity from fixation. By contrast, there is no consensus on what accounts for the two VP curve asymmetries for words. Moreover, no one account reliably predicts and thereby can explain the pattern of both the beginning vs end and left-to-center VP asymmetries observed across all stimulus strings. Let us consider the beginning vs end VP asymmetry. If what drives the VP asymmetries is the distribution of information as to the string's identity across its constituent characters, as proposed by the informativeness account, then there should be no asymmetry when informativeness is flat. On the contrary, however, we see the beginning vs end asymmetry for non-word letters and for letter-like character strings. Similarly, if what drives the VP asymmetries is left hemisphere dominance for word processing, as proposed by the cerebral laterality account, then there should be no VP asymmetries for any stimulus strings but words. Yet, contrast to this predication we do observe the beginning vs end VP asymmetry for pseudowords, strings of letter as well as strings of characters with letter-like features. By contrast, the perceptual learning account seems to do a good job of explaining the pattern of the beginning vs end asymmetry across all stimulus types.

Although neither can account for the beginning vs end VP asymmetry, both the informativeness and cerebral laterality accounts can explain the pattern of left to center OVP asymmetries, which is word specific (at least given the stimulus strings we have tested to date). By contrast, the perceptual learning account despite its success at explaining the beginning vs end asymmetries across stimulus cannot explain why only words show a left to center OVP. The relevant factors, reading experience with letter-like features and reading direction predict the left-to-center OVP for all string types except strings of characters which cannot be distinguished by letter like features (rings) but that is not we observe; neither the string of k' s nor those with characters having letter like features exhibit an asymmetric OVP. Moreover, my electrophysiological data reveal a word specific fixation effect: specifically, we see an effect of fixation position – smaller P1 component of the ERP at OVP than at center fixation, but only for words and only at the right occipital site, around 100 msec.

In short, on the one hand, it seems that across stimulus strings both cerebral laterality and informativeness can better account for the pattern of left-of-center OVP but perceptual learning can better account for the pattern of beginning vs end VP asymmetry. This suggests that potentially different mechanisms may be in play for the beginning vs VP asymmetry and the OVP asymmetry. I think that the correct account will adopt aspects each of the three extant accounts.

A tendency for better processing of strings with letter-like features in the right visual field (RVF) (while fixating the beginning of the string) than in the left visual field (LVF) (while fixating at the end of the string) is likely shaped by differential perceptual tuning through perceptual learning during the acquisition of reading skills. Moreover, our electrophysiological data suggest that the visual fields may interact with the nature of processing continuity between the fovea and parafovea. This interaction cannot be explained by the cerebral laterality account. According to the cerebral laterality account, left hemisphere specialization for language processing is responsible for the observed visual field asymmetry for both the beginning vs end VP asymmetry in the fovea and the RVF advantage for word processing in the parafovea (Brysbaert et al., 1996). If the left hemisphere is a responsible mechanism and the visual field difference reflects a delay due only to inter-hemispheric transfer from the right hemisphere (RH) to the left hemisphere (LH) for processing, the nature of the processing continuity between the fovea and parafovea should not interact with visual fields. It does! As the cerebral laterality and informativeness accounts both predict, the left-to-center OVP asymmetry is present only for words, consistent with word specific processing. Moreover, my electrophysiological data suggest that this word-specific process may occur relatively early, around 100 msec, which overlaps in time with perceptual processes, such as the length effect I observe. I speculate that this is when the impact of informativeness, presumably inherent in the sublexical structure across letter positions of the word, comes into play; this occurs sometime before the information moves along the ventral stream of the visual to the next more abstract word processing stage in the left visual word form as per the cerebral laterality account (Cai, Lavidor, Brysbaert, Paulignan, & Nazir, 2008; Cai, Paulignan, Brysbaert, Ibarrola, & Nazir, 2010). As visual word representation in skilled readers is presumably invariant to the word's physical parameters such as its location in visual space, researchers have suggested that an abstract word representation of this sort has been created by around 200 msec when information reaches the left visual word form area (Cohen et al., 2000; Cai et al., 2008; Brem et al., 2006). Little is known, however, about the time course and localization of the normalization processes during which location-specific (retinotopic) representations are transformed into location-invariant (word-centered) representations. Our finding of an OVP asymmetry for words only is the first apparent divergence between the processing of words and nonwords. This word-specific fixation effect suggests that location normalization for spatial (and perhaps size) invariance during visual word recognition may occur around 100 msec or so. In this way, the electrophysiological OVP effect speaks to not only the potential mechanisms for the VP asymmetries but also visual processes of invariance during word recognition more generally. To reiterate my position from the introduction – visual word recognition is a cognitive process subject to the properties of words, readers' brains, and interactions between these two (modified by experience), investigating VP curve asymmetries can provide a more integrative view of visual word representations and processing.

Note that although I point to the left-to-center OVP asymmetry as an instance of word specific processing, this is not intended to undermine my argument that word stimuli should be viewed as a visual object. We summarize our findings regarding each of the VP effects for each of the stimulus string types in a binary fashion – as observed or as absent. However, we are more interested in comparing and contrasting the patterns of all three VP effects across the various string types as it is this set of results that allows me to assess how each of the extant accounts fare in explaining them. Looking at the pattern of two asymmetric VP effects across the different string types overall, there emerges a gradient of progressively more word-like processing. As the stimulus varies from strings of characters without letter-like features to characters with letter-like features, the beginning vs end VP asymmetry emerges, which is best explained by perceptual learning; at the same time, the left-to-center OVP asymmetry emerges for words, which is equally well explained by informativeness and cerebral laterality (left hemisphere specialization for word processing). My thesis from these data is that all three of the accounts likely contribute to the VP effects albeit to varying degrees for different stimulus types (depending how word-like they are) and at different times (stages) during word processing in the ventral stream (Dehaene, Cohen, Sigman, & Vinckier, 2005). As perceptual learning is presumed to induce perceptual tuning in early visual areas (Karni & Sagi, 1991; Ball & Sekuler, 1982; Poggio, Fahle, & Edelman, 1992; Berardi & Fiorentini, 1987; Maffei & Fiorentini, 1976; McKEE & Westhe, 1978), we expect perceptual learning mechanisms to be engaged with the processing of letter-like features relatively earlier than the mechanisms involved in informativeness or cerebral laterality which bear greater responsibility for word-specific processing. If the fixation effect we observed on the P100 is indeed indicates a word specific effect, then letter strings of k and ring sequences like the nonwords should not show such an effect. Pseudowords, on the other hand, would be an interesting case to determine if the effect is modulated by different sublexical properties across the letter positions.

By employing a target discrimination task in a viewing position paradigm, I was able, to my knowledge for the first time, to discover an important role for a previously unexamined factor in the viewing position curve: visual crowding - the effect of the number of characters in the same visual field as the target. Visual crowding was found to influence all VP curves regardless of string types, asymmetrically for all VP curves except those to non-linguistic rings and words.

Large crowding effects for letters in the left visual field have been reported in the studies outside the scope of the viewing position effect (Bouma, 1973; Legge, Mansfield, & Chung, 2001; Tydgat & Grainger, 2009; Grainger, Tydgat, & Isselé, 2010; Chanceaux & Grainger, 2012). Larger crowding for letter strings in the LVF compared to the RVF is interpreted as reflecting special tuning of the receptive fields of stimuli that typically appear in strings (Tydgat & Grainger, 2009; Grainger et al., 2010; Chanceaux & Grainger, 2012). According to this modified receptive field hypotheses, the tuning involves location-specific letter detectors engaged in parallel letter recognition (Grainger & Van Heuven, 2003). We also observed a crowding asymmetry, larger in the LVF than RVF, for strings of characters constituted of letter-like features (symbol strings), which cannot be explained by tuning of hypothesized letter detectors. Moreover, the modified receptive field hypothesis cannot explain why words do not show greater visual crowding in the LVF than the RVF. My guess is that the null effect of crowding asymmetry for words and ring sequences do not result from the same mechanisms. Whatever the mechanism for words, it seems to improve letter recognition performance in the LVF and thereby lead to a diminution of the interference from the surrounding letters.

Our findings on crowding and crowding asymmetry indicate that visual crowding is an important factor in visual recognition generally including for the viewing position curve. It seems that the main factors driving the VP curve include visual acuity, visual crowding, and perhaps crowding asymmetry as well. I maintain that no complete model of the VP can ignore crowding. Visual crowding and visual crowding asymmetry, however, cannot be explained by either the informativeness or cerebral laterality account. Perceptual learning, on the other hand, although it does not currently have crowding as a variable, could potentially incorporate it.

In conclusion, while a complete model for the viewing position curve effects cannot yet be specified, with fine-grained measurements of recognition performance for a variety of more or less word-like stimuli, combing electrophysiological and behavioral approaches seems to offer critical observations for accessing the three main accounts for the VP asymmetries. The data suggests that two types of VP asymmetries, the beginning vs end and the left-to-center OVP asymmetry, could be due to different mechanisms that come into play at various processing stages. Consistently with this idea, the beginning vs end VP asymmetry is better explained by the perceptual learning account while the OVP asymmetry is better explained by the informativeness and cerebral laterality accounts. We suggest that each of proposed mechanisms might intervene in a temporal order associated with levels of processing, from perceptual to more or less word specific. Across the stimulus types, there seems to be modulations among the dependence of these candidate mechanisms. Stimulus characteristics matter, as does the functional organization of our brain and its experiences with reading materials.

Table 8.1: The observed effects for all types of the stimulus, ranging from words to incomplete ring sequences in this series of studies. "+" sign represents an observed effect and "-" sign represents the absence of effect.

Stimulus Types	**U-shape**	**Beginning vs end VP asymmetry**	**Left-to-center OVP asymmetry**	**Crowding**	**Crowding asymmetry between the visual fields**
Words	+	+	+	+	-
Pseudowords	+	+	-	+	+
Letter strings of ks	+	+	-	+	+
Symbol strings	+	+	-	+	+
Ring sequences	+	-	-	+	-

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