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Adapting to eccentric reading: visual and psycholinguistic constraints under simulated and pathological central visual field loss

Eole Lapeyre

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THÈSE DE DOCTORAT

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Eole LAPEYRE

Adapting to eccentric reading: visual and psycholinguistic constraints under simulated and pathological central visual field loss

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the Brain (ILCB)

Composition du jury

Miyoung KWON

Rapporteuse

Maître de conférence, Northeastern University, Boston, USA

Frédéric LAVIGNE

Rapporteur

Professeur, CNRS, Université Côte d'Azur, Nice

Pierre KORNPBST

Examineur

Directeur de recherche Inria, Université Côte d'Azur, Nice

Anna MONTAGNINI

Présidente du jury

Directrice de recherche, CNRS, Aix-Marseille Université

Aurélié CALABRESE

Directrice de thèse

Chargée de recherche, CNRS, Aix-Marseille Université

AFFIDAVIT

I, undersigned Eole Lapeyre, hereby declare that the work presented in this manuscript is my own work, carried out under the scientific supervision of Aurélie Calabrèse, in accordance with the principles of honesty, integrity and responsibility inherent to the research mission. The research work and the writing of this manuscript have been carried out in compliance with both the French national charter for Research Integrity and the Aix-Marseille University charter on the fight against plagiarism.

This work has not been submitted previously either in this country or in another country in the same or in a similar version to any other examination body.

Marseille, octobre 15th, 2025

A handwritten signature in black ink, reading "E. Lapeyre". The signature is written in a cursive style with a large, stylized initial "E".

PUBLICATIONS AND CONFERENCES

1.1 Publications

- Lapeyre, E., Calabrese, A. (in prep.). Assessing the influence of orthographic similarity when reading with eccentric vision: Coltheart's N against OLD20.
- Lapeyre, E., Gala, N., Calabrese, A. (2025). Beneficial influence of in-context predictability when young adults read with a simulated central scotoma. *Journal of Vision*, 25(10), doi:10.1167/jov.25.10.6.
- Lapeyre, E., Melmi, J-B., Cole, P., Calabrese, A. (2024). Pulsed lighting for adults with Dyslexia: very limited impact, confined to individuals with severe reading deficits. *Scientific Reports*, 14(1), doi:10.1038/s41598-024-73273-3

1.2 Conferences

1.2.1 Posters

- ARVO, Seattle, USA - 2024 – “Effect of word orthographic similarity when reading with a simulated central scotoma”
- Vision Research Network (GDR Vision) – 2024 – “Comparison of two orthographic similarity measures when reading with a simulated central scotoma”
- Science Fair, Marseille, France - 2023 – “The use of eye-tracking in vision research” (poster & demo)
- ARVO, New Orleans, USA - 2023 – “effect of word predictability on reading performance in normally sighted readers with a simulated scotoma”

1.2.2 Talks

- VISION 2025, Florence, Italy – “Influence of linguistic word features when reading with central vision loss”
- CENTAL Lab Seminar, Louvain-La-Neuve, Belgium - 2022 – “Automated Text Simplification as a reading aid for individuals with central field loss”

1.2.3 Attending

- GDR 2023.
- ILCB Summer School 2021, 2022, 2023.

1.3 English summary

In developed countries, central visual field loss (CVL) is the leading cause of visual impairment among people over 50, gradually causing them to lose the ability to read and recognize faces. CVL is caused by incurable retinal diseases such as diabetic maculopathy, myopic maculopathy, or age-related macular degeneration (AMD). Patients with these conditions develop a blind spot called a scotoma, located in the center of their visual field, up to 20°.

Forced to rely on their peripheral vision, most affected individuals eventually develop one (or more) peri-foveal regions outside the damaged area that they preferentially use to focus, known as the Preferred Retinal Locus (PRL). Despite these adaptive strategies, reading – a complex task involving both visual and cognitive processes – becomes the primary complaint of patients. Over 30% of them eventually give up daily reading activities altogether, and the underlying causes of this deficit remain poorly understood.

Due to the aging population and its strong correlation with the prevalence of eye diseases, the number of patients affected by CVL is expected to increase in the coming years (60 million in Europe / 288 million worldwide by 2030). Given its significant importance for quality of life and independence, the ability to read must be preserved at all costs for these individuals. Therefore, there is a real societal need to overcome their difficulties and restore their (fluent) reading abilities.

This dissertation proposes an innovative and multidisciplinary approach aimed at better understanding the underlying causes of poor reading performance in individuals affected by CVL, combining psycholinguistic and visual approaches. By investigating the influence of lexical, semantic and visual factors, the aim of this work was twofold: 1) to identify the psycholinguistic factors that significantly influence reading performance in the presence of a central scotoma, and 2) to highlight their impact on the oculomotor and visuo-attentional strategies that affected individuals use during reading to compensate for their impairment.

Using a psychophysical approach, we conducted a series of experiments to examine sentence reading performance and eye-movement behavior in both patients with CVL and normally sighted adults reading with a gaze-contingent simulated scotoma. The results showed that the key psycholinguistic variables known to most influence normal reading also strongly modulate reading under central vision loss. In addition, we developed and validated novel metrics of visual ambiguity based on letter-shape similarity, revealing that the visual confusability of letters and words contributes to reading difficulty independently of classical lexical properties. These psycholinguistic and visual effects were observed across both young and older readers; however, older adults – particularly those with pathological CVL who had reduced reading practice – showed slower adaptation and relied more on word-by-word (length-based) strategies. Analysis of eye movements further characterized the adaptive oculomotor responses enabling eccentric reading, notably the development of pseudo-PRLs and specific fixation patterns allowing eccentric reading.

As this is the first work to comprehensively characterize psycholinguistic influences on reading in a low-vision population, it provides novel insights into the interplay of high-level linguistic cues and low-level visual constraints in reading, and highlights the plasticity of oculomotor strategies that support fluent reading despite central visual field loss.

Keywords: reading, eye movements, reading impairment, central vision loss, psycholinguistics, simulated scotoma

1.4 Résumé français

Dans les pays développés, la perte de vision centrale représente la première cause de handicap visuel chez les plus de 50 ans, entraînant peu à peu la perte de la capacité à lire et à reconnaître les visages. Elle résulte de pathologies rétinienne incurables telles que la maculopathie diabétique, la maculopathie myopique ou la Dégénérescence Maculaire Liée à l'Âge (DMLA). Ces pathologies provoquent l'apparition d'une tache aveugle appelée scotome, située au centre du champ visuel et s'étendant jusqu'à 20°.

Forcés d'utiliser leur vision périphérique, la plupart des individus atteints développent une (ou plusieurs) région péri-fovéale en dehors de la lésion, utilisée préférentiellement pour fixer appelée PRL (Preferred Retinal Locus). Malgré ces stratégies d'adaptation, la lecture – tâche complexe mobilisant à la fois les processus visuels et cognitifs – demeure la plainte principale des patients. Plus de 30 % abandonnent même toute activité quotidienne de lecture, et les causes précises de ce déficit restent mal identifiées.

En raison du vieillissement de la population et de sa forte corrélation avec la prévalence des maladies oculaires, le nombre de patients atteints de perte de vision centrale continuera d'augmenter dans les années à venir (60 millions en Europe, 288 millions dans le monde d'ici 2030). Compte tenu de son rôle essentiel pour la qualité de vie et l'autonomie, le maintien des capacités de lecture chez ces personnes constitue un enjeu sociétal majeur.

Ce travail de thèse adopte une approche novatrice et multidisciplinaire pour mieux comprendre les causes des faibles performances de lecture liées à la perte de vision centrale, en combinant analyses psycholinguistiques et visuelles. En étudiant l'impact de facteurs lexicaux, sémantiques et visuels, cette recherche visait : 1) à identifier les facteurs psycholinguistiques influençant significativement la lecture en présence d'un scotome central ; 2) à préciser leur effet sur les stratégies oculomotrices et visuo-attentionnelles mises en place pour compenser la perte fovéale.

À l'aide d'une approche psychophysique, plusieurs expériences ont examiné la lecture de phrases et les mouvements oculaires chez des patients atteints de perte de vision centrale et chez des adultes à vision normale lisant avec un scotome central simulé. Les résultats montrent que des variables psycholinguistiques clés modulent fortement la lecture en cas de perte de vision centrale. Nous avons également développé de nouveaux indices d'ambiguïté visuelle basés sur la similitude des lettres, révélant que la confusion visuelle contribue aux difficultés de lecture indépendamment des propriétés lexicales classiques. Ces effets ont été observés chez les lecteurs jeunes et âgés ; toutefois, les plus âgés, en particulier les patients ne lisant plus quotidiennement, ont montré une adaptation plus lente et davantage basé sur un déchiffrement mot à mot. L'analyse des mouvements oculaires a permis de caractériser les ajustements oculomoteurs favorisant la lecture excentrique, notamment le développement de pseudo-PRL et de patterns oculomoteurs adaptés à la lecture excentrée.

Ce travail, premier à décrire de manière exhaustive les influences psycholinguistiques sur la lecture en population malvoyante, met en lumière l'interaction entre contraintes linguistiques et visuelles, ainsi que la plasticité des stratégies oculomotrices qui permettent de maintenir une lecture fonctionnelle en vision excentrée.

Mots-clés : lecture, mouvements oculaires, perte de la vision centrale, psycholinguistique, scotome simulé

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Preamble

Have you ever imagined what life would be like if the very center of your visual world suddenly disappeared? Central visual field loss affects many aspects of daily life, from recognizing faces to safely navigating a busy street. Yet, for most people with this condition, the greatest challenge is reading. Access to written information is essential for independence and leisure; losing it threatens both practical functioning and quality of life. Throughout this manuscript, central visual field loss is abbreviated as CVL (also referred to as CFL in the literature).

Because reading difficulties in CVL stem from a visual deficit, most studies and rehabilitation programs understandably focus on visual solutions, e.g., enlarging letters, increasing contrast, or changing text layout. However, reading is not only a visual process: the meaning and structure of words also influence how quickly and accurately our eyes move across the page. This raises the central question of this dissertation: beyond the visual constraints typically targeted in low vision rehabilitation, to what extent do the psycholinguistic properties of text influence reading when central vision is compromised? Accordingly, the overall aim of this dissertation is to quantify how visual degradation and psycholinguistic constraints interact to affect reading, and to identify the adaptive oculomotor strategies that allow individuals to sustain reading despite central vision loss.

Identifying the role of these psycholinguistic constraints could guide the creation of linguistically simplified materials that would help individuals with CVL continue to read for both necessity and enjoyment. By sustaining the habit of reading (even with simplified material) one can hope to preserve reading skills over time and help individuals maintain independence in their daily activities.

Dissertation outline

This dissertation is organized in four main parts.

Part I – Theoretical and methodological framework

Part I establishes the theoretical and methodological foundations of the thesis. Chapter 1 begins by describing the main visual mechanisms involved in reading and how they are affected when central vision is lost. It also reviews experimental evidence from studies using simulated scotomas and presents the main research questions that structure the dissertation. Chapter 2 details the methodological framework shared across all studies, including the experimental setup, linguistic material, and analysis procedures used throughout the work.

Part II – Disentangling psycholinguistic complexity in eccentric reading

Part II examines how psycholinguistic factors shape reading when central vision is unavailable. Chapter 3 investigates the effect of contextual predictability on reading with a simulated scotoma. Chapter 4 compares several measures of orthographic similarity to determine how they affect recognition under degraded vision.

Part III – Bridging the gap psycholinguistic complexity and visual ambiguity

Part III focuses on visual aspects of word identification and their interaction with psycholinguistic variables. Chapter 5 introduces and validates two new visual metrics – the Word Ambiguity Measure (WAM) and VA20 – that quantify letter-level confusability. Chapter 6 extends the investigation of all previously studied predictors across age and vision conditions, comparing reading performance in young and older adults under simulation and in older adults with acquired CVL.

Part IV – Exploring adaptive reading strategies in eccentric reading

Part IV investigates how readers adapt their eye movements when foveal vision is lost. Chapter 7 analyzes fixation behavior to identify Preferred Retinal Loci (PRLs) and other compensatory strategies. And finally, the general discussion integrates the findings from all studies, discussing their theoretical and methodological implications, and concludes by outlining perspectives for improving reading rehabilitation and text accessibility for individuals with CVL.

Part I - Theoretical and methodological framework

Chapter 1 GENERAL INTRODUCTION

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1 Vision

Having outlined the societal stakes of studying central visual field loss, the next section describes the normal visual system to clarify how central and peripheral vision support these everyday tasks. Vision is a primary sense through which humans interact with their environment. From navigating daily life to recognizing faces and reading text, our ability to extract information from the visual world depends on the remarkable organization of the eye, and particularly the retina. This structure is not uniform: different regions are specialized to serve distinct functions, from processing fine details in the center, to supporting spatial awareness and motion detection in the periphery.

1.1 General definitions of vision

1.1.1 Anatomically

The human eye is a complex optical system. Light passes through the cornea and lens, which focus the image onto the retina at the back of the eye (Figure 1.1 - left). The retina is a layered neural tissue in which photoreceptors convert light into electrical signals that are transmitted to the brain via the optic nerve. Within the retina, the fovea occupies a central position (Figure 1.1 – right) and contains the highest density of cone photoreceptors (Curcio & Allen, 1990).

Surrounding the fovea, the parafovea extends to about 5° of visual angle and still contains a high proportion of cones, though fewer than in the foveal pit. Beyond this region, cone density declines sharply while rod density increases (Figure 1.2). This anatomical organization establishes the distinction between central and peripheral regions of the retina.

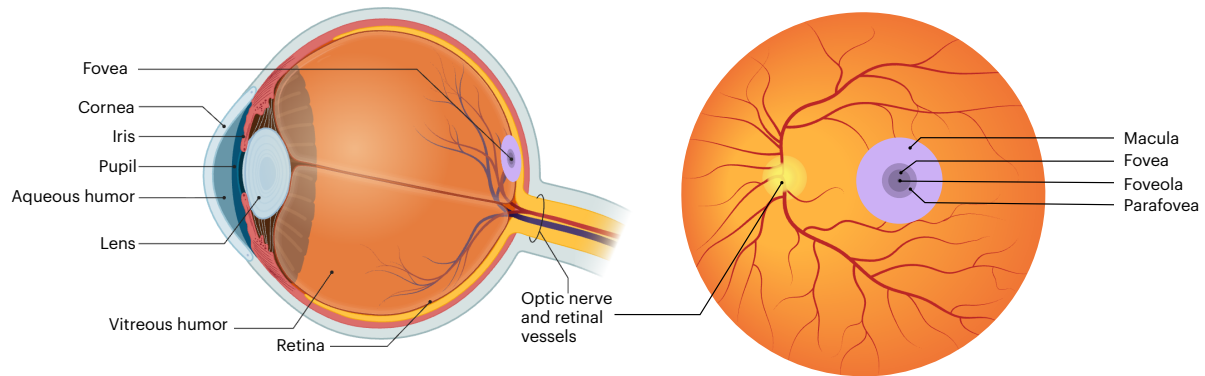


Figure 1.1 Sagittal section of the human eye (a), and sketch of a healthy eye fundus (inside, back surface of an eye), i.e., the retina. Both sketches show the macula and the fovea in light and dark purple.

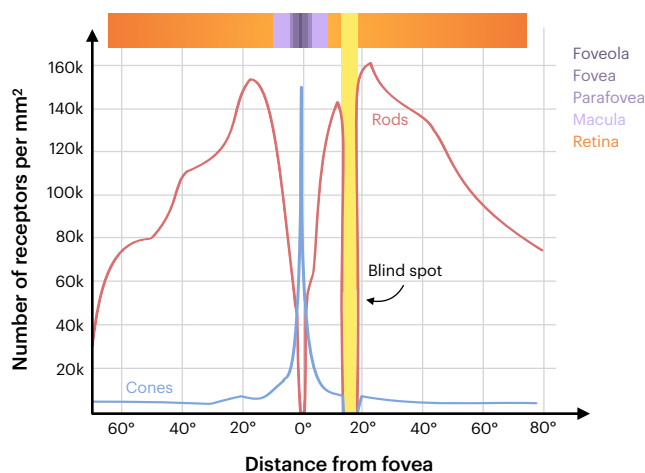


Figure 1.2 Distribution of photoreceptor cells (rods and cones) across the retina. The blind spot around 12-15° of eccentricity from the fovea is represented in yellow and corresponds to an area with no photoreceptor cells due to the location of the optic nerve. The gradient horizontal ribbon shows the location of the retina, macula and fovea on the angular degree scale.

1.1.2 Functionally

The anatomical specialization of the retina translates into distinct perceptual roles. The central retina (macula and fovea) provides fine spatial resolution, rapid signal processing, and high visual precision. It supports detailed perception, such as color discrimination and optimal visual acuity. In contrast, the peripheral retina, dominated by rods, is less precise but optimized for global monitoring of the environment. It provides a wide visual field, is highly sensitive to motion, and remains efficient in low-light conditions.

At the functional level, these differences explain why tasks that require fine detail – such as recognizing faces or reading – depend primarily on central vision, whereas tasks involving spatial orientation and motion detection rely more on peripheral vision.

1.2 Normal changes with age

Visual function naturally evolves with age, even in the absence of pathology. Presbyopia, for example, reduces the ability to focus on near objects (Atchison, 1995). In addition, visual acuity gradually declines across adulthood, although most older adults maintain at least fair acuity (20/40 or better) into their 80s (Gittings & Fozard, 1986). Older adults also experience reduced contrast sensitivity (Owsley, 2011) and general declines in processing speed (Salthouse, 1996). Reading performance also becomes less efficient with age, especially under dim lighting or with small print sizes (Calabrèse, Cheong, et al., 2016). While these non-pathological changes may not prevent reading altogether, they contribute to greater visual effort and fatigue during sustained reading.

1.3 Pathological changes with age

Beyond normal aging, several ocular diseases, called maculopathies, can lead to central visual field loss (CVL) by damaging the macula and impairing central vision. Among these, Age-related Macular Degeneration (AMD) is by far the most prevalent in industrialized countries and the leading cause of severe vision loss in individuals over 60 (Wong et al., 2014). Current estimates suggest that AMD affects more than 200 million people worldwide, and could reach about 300 million by 2040 as populations age (Vyawahare & Shinde, 2022). About 88% of patients with AMD present binocular scotomas, which are blind spots in the center of the visual field. 66% of scotomas are dense (absolute) (Fletcher et al., 2012), meaning that no visual information can be detected in the affected area. There are two forms of AMD.

The dry form (also called atrophic or non-neovascular AMD) which accounts for roughly 80–90% of cases and progresses slowly. It is characterized by a degeneration of the retinal pigment epithelium (RPE) and the photoreceptors it supports (Figure 1.3 - left). Metabolic wastes accumulate between the RPE and Bruch's membrane, forming drusen, which are deposits that disrupt nutrient exchange. Over time, the RPE and overlying photoreceptors become thinner and die, producing areas of geographic atrophy. These atrophic patches correspond to central scotomas where photoreceptor signals no longer reach the optic nerve. Currently, there is no available treatment for dry AMD. However, there is evidence that not smoking, exercising regularly, eating nutritious food, and taking certain supplements can reduce the risk of acquiring dry AMD or slow its development (Marchesi et al., 2024).

The wet form (also called neovascular or exudative AMD) is less common but causes most cases of rapid, severe vision loss. In this form, fragile new blood vessels grow from the choroid through small breaks in Bruch's membrane into the space under the RPE (Figure 1.3 - right). These abnormal vessels leak fluid or blood, swelling the macula, and separating photoreceptors from their support. This creates scar tissue that permanently damages the

RPE and photoreceptors. Today, repeated intravitreal injections of anti-VEGF drugs can slow this abnormal vessel growth.

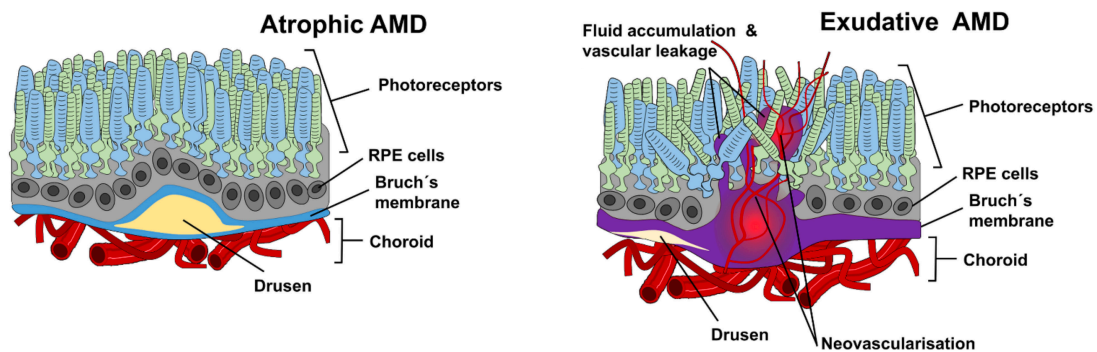


Figure 1.3 Schematic representation of the structural retinal abnormalities associated with each type of AMD. Atrophic AMD is associated with drusen accumulation, Bruch's membrane alteration and RPE modifications. Exudative AMD is associated with neovascularization, fluid accumulation and vascular leakage. Figure adapted from (Bobadilla et al., 2022).

Apart from AMD, other conditions leading to CVL include diabetic retinopathy, which can produce macular edema, and severe myopia, which predisposes to myopic macular degeneration (Bourne et al., 2014). Less common but clinically important causes include hereditary macular dystrophies such as Stargardt or Best diseases (Altschwager et al., 2017).

These pathologies primarily damage the macula, the most acute region of central vision. Consequently, the first and most frequent clinical complaint of patients with CVL is the difficulty or inability to read fluently (Brown et al., 2014; Kanonidou, 2011). Because reading is one of the most demanding central-vision tasks, these conditions offer a natural model to study how the visual system adapts to the absence of central input and how this adaptation affects complex tasks like reading.

2 Reading

In this dissertation, I take advantage of this model to investigate the mechanisms of reading without central vision. To do so, we must first understand how reading normally operates across the life span, both at the low-level (visually) and at the high-level (linguistically), before examining how these processes are disrupted by central visual field loss.

2.1 Normal reading

Fluent reading involves highly coordinated oculomotor behaviors (Figure 1.4): sequences of forward saccades and fixations that allow the reader to efficiently extract visual information

across a line of text (Rayner, 1998). These movements are not random (Rayner & McConkie, 1976). Saccades are rapid jumps, typically spanning 2° of visual angle (\approx 8 characters for typical book or newspaper print at a normal reading distance) and lasting 20–40 ms, during which visual input is unavailable (Rayner, 1998). In between saccades, the gaze is stable and allows for the extraction of visual information; this period is called a fixation and averages around 225 ms. When reading out loud, both saccades and fixations are longer; saccades span only 1.5° of visual angle (\approx 6 characters) and fixations last on average 275 ms. Most saccades are progressive – they move forward along the line of text –, but around 10 to 15% of saccades are regressive – they move backward, often to re-inspect difficult or ambiguous parts of text (Vitu & McConkie, 2000). Especially long saccades are needed to drag the gaze from the end of a line of text to the beginning of the next. During reading, the eyes also exhibit small drifts and microsaccades, serving two functions: (a) an intra-word saccade correction function, to view the word at the optimal viewing position (OVP), and (b) a preceding-word exploration, when long saccades skip over words (N. R. Bowers & Poletti, 2017).

When a person is reading a sentence silently, the eye movements show that not every word is fixated. Every once in a while a regression (an eye movement that goes back in the text) is made to re-examine a word that may have not been fully understood the first time. This only happens with about 10% of the fixations, depending on how difficult the text is. The more difficult the higher the likelihood that regressions are made.

Figure 1.4 Ocular movement during reading. Fixations are represented by orange circles and saccades are represented by straight lines between fixations.

Fast readers tend to make shorter fixations, longer saccades, and fewer regressions than slow readers. Although older adults often exhibit eye-movement patterns characteristic of slower reading - longer fixations and more regressions (Kliegl et al., 2004a) - their mean reading speed remains comparable to that of younger adults when print size and text difficulty are favorable. Under more demanding conditions (e.g. smaller print, rare words, complex syntax), however, their reading speed declines more sharply, revealing age-related limitations in adaptability despite overall preserved performance (Risse & Kliegl, 2011).

Eye-movement patterns are ultimately constrained by how much text can be seen and identified during each fixation, a limit captured by the concepts of visual and perceptual span.

2.1.1 Visual and perceptual span

Because acuity declines sharply with retinal eccentricity, readers can recognize only a limited number of letters during a single fixation. This limit is captured by two related concepts. The visual span refers to the number of letters that can be identified in a non-linguistic task under optimal conditions (Legge et al., 1997). The perceptual span is measured during natural reading and represents the area from which readers extract useful information: it is asymmetric, typically extending 3 to 4 letters to the left and 14 to 15 letters to the right of a fixation (Rayner, 1986). Importantly, the perceptual span is not fixed: when text is more difficult it often becomes smaller, presumably because increased processing demands on the fixated word reduce the attentional resources available for parafoveal processing (Henderson & Ferreira, 1990; Rayner, 1986). Together, these spans strongly constrain reading speed because they determine how much information (from text) can be processed before the next saccade.

2.1.2 Psycholinguistic processing

Reading is not just a sequence of eye movements; it is driven by rapid lexical and contextual computations. During each fixation, the visual input must be transformed into an internal word representation through lexical access. Several word-level properties have been reported to strongly influence fixation durations and skipping behavior in normal adult readers. Keith Rayner referred to three of these variables - frequency, length, and predictability in context - as the 'Big three' factors in reading (Rayner, 1998), which are the most extensively studied parameters influencing reading time. Other factors, such as orthographic similarity, have also been extensively studied in normal reading.

Word frequency refers to how often a word occurs in the language (usually expressed as occurrences per million words in a large corpus). High-frequency words such as "stop" (≈ 700 per million) are recognized more quickly than low-frequency words such as "halt" (≈ 11 per million), leading to shorter fixations and more frequent skipping (Kliegl et al., 2004a; Rayner et al., 2011), even when the preview is masked (Inhoff & Rayner, 1986).

Word predictability captures how well a word fits the preceding sentence context. For example, in "The dog barks" the final word is highly predictable, whereas in "The child barks", the very same word is not highly predictable, even though the sentence remains semantically plausible. Highly predictable words are read faster and skipped more often, even when visual information is degraded (Ehrlich & Rayner, 1981).

Word orthographic similarity, which measures the span of a word's orthographic neighborhood, can be expressed in different ways. Coltheart's N refers to the size of a word's orthographic neighborhood (i.e., its number of neighbors) by measuring how many words can be produced by switching a single letter while preserving letter positions and word length (Coltheart et al., 1977). A word like "danger" (neighbors: dancer, ranger, hanger ...) has a large neighborhood ($N = 9$), whereas its synonym "hazard" has no strict neighbor ($N = 0$). Large

neighborhoods generally facilitate recognition by speeding lexical access in normal reading (Andrews, 1997; Perea & Rosa Martínez, 2000). Because Coltheart’s N is restricted to single-letter substitutions (i.e. the strict definition of orthographic neighborhood), it fails to capture graded similarities or neighbors formed through insertions, deletions, or transpositions, and it quickly collapses to zero for long or unusual words. To overcome these limitations, Yarkoni et al. (2008) introduced a broader measure of orthographic similarity: OLD20 (Orthographic Levenshtein Distance 20). OLD20 calculates the average number of single-letter edits (insertions, deletions, and/or substitutions) needed to change a word into its 20 closest neighbors, thus considering a broader and more nuanced set of similar words, including those of different lengths. Smaller OLD20 values indicate denser orthographic neighborhoods, while larger values signal sparser neighborhoods (Table 1.1). In young healthy readers, OLD20 explained more variance as to how people recognize and process written words than Coltheart’s N (Yarkoni et al., 2008).

And finally, word length, is simply the number of letters composing a word. One of the most robust findings in research on eye-movement control in reading is that short words such as “job” (3 letters) are recognized and processed faster (i.e. with shorter fixations or higher skipping over rate) than longer synonyms, such as “occupation” (10 letters) (New et al., 2006).

CONDITION	PISTACHIO
Distance = 1 conditions	Distance = 1 —
Distance = 2 coalition, cognition, conditional, conditioned, conditioner, conduction, contrition, conviction, recondition, rendition	Distance = 2 —
Distance = 3 addition, audition, collation, collision, commotion, conception, concoction, concretion, conditioners	Distance = 3 —
	Distance = 4 distraction, hibachi, mustache, mustached, mustaches, pigtail, pistil, pitch, pitched, pitcher, pitches, pitching, psychic, psycho
	Distance = 5 abstain, abstraction, antacid, attach, attache, attached
OLD20_{CONDITION} = 2.4	OLD20_{PISTACHIO} = 4.3

Table 1.1. Examples of the twenty closest Levenshtein neighbors for the words CONDITION and PISTACHIO. For CONDITION, the mean orthographic Levenshtein distance across its twenty closest neighbors (OLD20 = 2.4) indicates a dense orthographic neighborhood. In contrast, PISTACHIO has a higher OLD20 value (4.3), reflecting a sparse neighborhood with few closely related word forms. Table adapted from (Yarkoni et al., 2008)

2.1.3 Models of lexical access and word recognition

To account for these robust effects of frequency, predictability, neighborhood size and length, several computational models of reading describe how visual input is transformed into lexical representations and ultimately, into meaning.

The activation-based models propose that seeing a word activates its mental representation; the more active a word becomes, the sooner it is recognized. The Logogen model posits that frequent words start from a higher level of activation. Consequently, they reach the recognition point faster than rare words (Morton, 1969). The interactive activation model posits that letters and whole words activate each other at the same time: common words or neighbors gain more activation, which explains the effects of frequency and orthographic neighborhood size described above (McClelland & Rumelhart, 1981).

On the other hand, the dual-route models suggest that words are recognized using two parallel pathways. The dual-route cascade model proposes a fast lexical route, allowing direct recognition of familiar words, and a slower sub-lexical route for unfamiliar words, converting letters into sounds step by step (Coltheart et al., 2001). Familiar words can be read by both routes (short reading time) whereas unfamiliar words, irregular words (words with mismatched spelling-sound, e.g. *yacht*) or non-words can only be read correctly by the sub-lexical route (longer reading time). In this model, word length particularly slows reading for unfamiliar words that must be decoded letter by letter, while it has little effect on familiar words that are recognized directly. Grainger and Ziegler's Coarse/Fine dual-route model focuses on two types of sub-lexical routes (Grainger & Ziegler, 2011). It posits a coarse pathway, which uses approximate letter order for fast identification, and a fine pathway, which relies on precise letter identity and position. In normal readers, both routes are used in parallel, supporting fast and accurate reading.

2.1.4 Models of eye-movement control

While word recognition models describe how text is processed, models of eye-movement control explain how visual and linguistic information jointly determine when and where the eyes move during reading – which are largely independent of each other (Rayner & Pollatsek, 1981). Regarding “where” the eyes land, readers typically fixate around one third into a word (OVP) (Rayner, 1979), and landing sites are normally distributed because of oculomotor errors (McConkie et al., 1988). This suggests that landing position on text is largely determined by visual and oculomotor constraints. As for “when” the eyes land on text, fixations are influenced by higher-level cognitive processing, including the psycholinguistic properties of words.

Computational models of reading combine visual and linguistic factors to explain where and when we move our eyes while reading. The E-Z Reader model assumes that words are processed one after another (serial processing). According to this view, the gaze moves to the next word as soon as the current word has been recognized (i.e. familiarity check). Then, while the next word's saccade is being prepared, the ongoing word is identified/processed (Reichle et al., 2003). In contrast, the SWIFT model assumes that several words are processed in parallel. It describes attention spreading across several nearby words at once, while an internal timer triggers saccades at regular intervals (Engbert et al., 2005). When text is more difficult, the timer slows down. When it is time to trigger a saccade, the oculomotor system selects a target probabilistically, based on parafoveal processing.

A more recent model blends serial and parallel processing together. In the OB1-Reader model, it is believed that while fixating, readers form quick, rough guesses of a few words nearby, at the same time (i.e. in parallel). Words that are fully identified parafoveally are skipped, while words that are only partly identified are the most likely next fixation targets (Snell et al., 2018).

While these three models differ, they all provide an explanation of the classic findings regarding the effects of word frequency, contextual predictability, and the benefit of seeing upcoming words (parafoveal preview) on fixation durations and skipping rates. On the other hand, the MASC model (Model of Attention in the Superior Colliculus) has challenged the notion that lexical processing directly drives eye movements during reading. MASC is a model that uses only low-level visual and oculomotor principles to generate realistic reading-like paths without incorporating any lexical or linguistic variables (Adeli et al., 2017; Vitu et al., 2016). Because MASC reproduces hallmark reading patterns without incorporating lexical information, it proposes that eye movements can be explained by low-level visuomotor dynamics alone. This view is controversial because it contrasts sharply with models such as E-Z Reader and SWIFT, which attribute a central, causal role to lexical processing in controlling saccade timing and targeting.

Aside from these literature controversies, most models reach consensus on three points:

- Lexical processing - how quickly a word is recognized - is the main driver of fixation time.
- Parafoveal preview - the ability to gather information from the next word before fixating it - is crucial for fluent reading.
- Both visual constraints and linguistic context jointly shape eye-movement control, even though the exact amount of parallel word processing remains debated (Reichle, 2021).

				Model predictions		
				Frequency	Predictability	Orthographic Similarity
Activation-based models: single activation route from perception to recognition. In Logogen, activation is mostly bottom-up; in Interactive activation, activation is dynamic in both bottom-up and top-down directions.						
Logogen (Morton, 1969)	High-frequency words have lower activation thresholds, so they reach recognition faster	Context pre-activates relevant logogens, facilitating activation of the target word	No explicit prediction			
Interactive Activation Model (McClelland & Rumelhart, 1981)	High-frequency words start with higher resting activation, facilitating recognition	No explicit prediction			Low-frequency words are facilitated by dense neighborhood, but high-frequency words can be inhibited by strong competitors with overlapping letters	
Dual routes models: two distinct but cooperating pathways – a fast lexical route enabling direct access to familiar words, and a slower, more precise sub-lexical route converting letters to sounds for unfamiliar or novel items.						
Dual-Route Cascade (Coltheart et al., 2001)	High-frequency words have higher resting activation in the orthographic lexicon	No explicit prediction			Orthographic similarity inhibits recognition by causing competition among similar entries	
Coarse/ fine dual route (Grainger & Ziegler, 2011)	Frequency shapes both routes: the coarse route relies on common patterns, while the fine route processes distinct or rare ones	No explicit prediction			Moderate overlap between words produces facilitation (shared bigrams) and excessive overlap leads to inhibition (competition).	
Models of eye movement control: describe how lexical and visual information jointly determine when and where the eyes move during sentence reading.						
EZ-Reader (Reichle et al., 2003)	Frequency reduces lexical processing time, leading to shorter fixations	Predictable words reach the “familiarity check” stage sooner, prompting earlier saccade initiation and higher skipping rates	No explicit prediction			
SWIFT (Engbert et al., 2005)	Frequency increases lexical activation rate leading to shorter fixations and more skipping	Predictability speeds up processing for expected words even for parafoveal processing	No explicit prediction			
OB1-Reader (Snell et al., 2018)	High-frequency words have lower recognition thresholds, speeding recognition	Sentence context pre-activates likely upcoming words, facilitating recognition and influencing fixation targeting.			High-frequency neighbors can inhibit recognition through competition. In addition, dense neighborhoods lengthen gaze durations.	
MASC (Adeli et al., 2017)	No influence of frequency on eye movements during reading	No influence of predictability on eye movements during reading	No influence of orthographic similarity on eye movements during reading			

Table 1.2 Summary of principal computational models of lexical access and eye-movement control in reading. Green boxes indicate a facilitatory effect of the factor, red boxes an inhibitory effect, and orange boxes a possible mix of facilitation and inhibition depending on context. Grey boxes indicate that the model does not make an explicit prediction or that no influence is expected.

These mechanisms, established for normal reading provide a theoretical foundation for understanding how they may be altered when central vision is lost. Because foveal vision is critical for high-acuity detail and for the rapid lexical processing that drives eye-movement control, damage to this region profoundly disrupts the reading process. Psycholinguistic

predictions from main models of reading have been summed up in Table 1.2. The following section examines how these processes break down and adapt when foveal input is no longer available.

2.2 Reading with CVL

Building on the principles outlined in the previous section, this section examines how the loss of central vision affects the visual, oculomotor and psycholinguistic mechanisms that support reading.

2.2.1 Behavioral consequences of pathological CVL on reading

Central visual field loss (CVL) profoundly disrupts the reading process and is consistently reported as one of the most disabling consequences of macular diseases (Brown et al., 2014; Kanonidou, 2011). Patients typically read at much slower speeds than normally sighted individuals, often reduced by more than half, even when text size is increased (Cummings et al., 1985; Legge et al., 1985; H. Yu & Kwon, 2023). Because reading depends on rapid and precise oculomotor processes, these dysfunctions greatly impair fluency and comprehension.

Such difficulties are reflected in both controlled studies and daily reading activities. Patients frequently report difficulties accessing everyday texts such as newspapers, books, medication labels, or digital displays, which reduces independence and overall quality of life. Even highly motivated readers who adopt compensatory strategies rarely regain normal reading speed.

2.2.2 Impact of visual factors

The poor reading performance of CVL patients has been extensively investigated from a visual perspective. In normally sighted readers, reading speed decreases systematically as text is presented at increasing eccentricities (Legge et al., 2001). This provides a useful model for understanding the limitations of eccentric vision, which becomes the primary source of information when central vision is lost. Several well-documented mechanisms contribute to the difficulty of reading with eccentric vision.

Visual crowding makes it harder to identify a letter when it is surrounded by adjacent letters - an issue that is far more severe in the peripheral field than in the fovea (Levi, 2008; Pelli et al., 2007), and becomes even stronger with age (Liu et al., 2017). The visual span also shrinks with eccentricity, reducing how much information can be processed at once and directly limiting reading speed (Legge et al., 2001).

Damage to the macula also lowers contrast sensitivity, diminishing sensitivity to fine detail and making letter recognition more difficult and thus, slower (Rubin & Legge, 1989). Finally,

many patients show fixation instability; their eyes have difficulty holding a steady gaze. Small, unintended eye movements cause the fixation to drift, which disrupts the visual input, causing disruption in letter recognition and also leading to slower reading (Crossland et al., 2004).

Various text-formatting have been explored to improve reading performances when central vision is deficient. Increasing print size improves performance up to a critical point where reading speed plateaus (S. T. Chung et al., 1998; Legge et al., 1985). Adjusting inter-line spacing can reduce crowding and improve comfort (J.-B. Bernard et al., 2007; Calabrèse et al., 2010). Alternative presentation modes such as rapid serial visual presentation (RSVP) or scrolling text have also been tested (A. R. Bowers et al., 2004; Walker et al., 2016). Different fonts have also been largely investigated (J.-B. Bernard et al., 2016; Mansfield et al., 1996; Rubin et al., 2006; Tarita-Nistor et al., 2013). While these manipulations yield modest benefits, none restore reading to normal levels (S. T. L. Chung, 2020). Some other manipulations of text simply did not show significant improvement in reading with CVL, such as displaying bolder text (S. T. L. Chung & Bernard, 2018) or displaying text vertically (Calabrèse et al., 2017; Subramanian et al., 2010).

Alongside these empirical approaches, a few models have sought to predict or optimize reading strategies when visual input is degraded. The ideal-observer model developed by Bernard and collaborators (2008) estimates where a reader should look to see the letters as clearly as possible (J.-B. Bernard et al., 2008). The model takes into account how letter visibility changes across the visual field and predicts the eye position that provides the clearest overall view of the text. When applying a simulated central scotoma, the model often selects a fixation position above or below the line of text, indicating that the most efficient reading strategy may involve a vertical shift of the retinal locus. The Mr. Chips model is a different ideal-observer model of reading that accounts for visually degraded input. Instead of predicting where to look, Mr. Chips estimates the fastest possible reading speed given the quality of the visual input. It calculates how quickly letters can be identified across the visual field. The model postulates that reading speed is limited by two key factors: the visual span and the accuracy of letter recognition at each retinal location. By combining these two measures, Mr. Chips predicts a theoretical upper limit for reading performance and demonstrates how reductions in visual span or letter recognition in the periphery can slow reading (Legge et al., 2002). Together, these models provide a solid oculomotor framework for studying reading with CVL.

However, they do not focus on the psycholinguistic content of text itself. A pivotal study by Calabrèse and colleagues (2016) highlighted this gap. Using detailed eye-tracking, they examined how fixations were distributed along sentences read by patients with macular degeneration (Calabrèse, Bernard, et al., 2016). They found that the psycholinguistic properties of the words - and not just the quality of the visual input - can strongly influence where readers look and how long they spend on each word. They revealed that low-frequency words trigger clusters of fixations yielding longer reading times, highlighting the powerful role of psycholinguistic factors in reading with CVL. This study bridged the fields of low-vision rehabilitation and psycholinguistics, laying the groundwork for investigations of how lexical and contextual factors influence reading in CVL. These investigations are the focus point of

the present PhD work, which will help provide insight into the challenges encountered when reading with central vision loss.

2.2.3 Impact of psycholinguistic factors

In normal vision, three psycholinguistic variables - word frequency, predictability in context and length - are among the strongest determinants of reading time. Recent evidence indicates that these factors play an even greater role when central vision is compromised.

Stolowy et al. (2019) showed that the word frequency facilitation is stronger in French CVL readers than in controls (Stolowy et al., 2019). Word length, which has only been controlled for as a covariate in studies focusing on other psycholinguistic factors, also showed a robust effect: longer words elicited longer fixation durations and more fixations in patients, and this effect is stronger in CVL patients than in controls (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019).

On the other hand, the reported impact of predictability when reading with CVL is mixed: some studies report context benefits comparable to controls (Fine & Peli, 1996; Legge et al., 2002) or comparable in healthy reader's central versus peripheral visual field (Fine, Hazel, et al., 1999). Others suggest an even stronger reliance on context when visual input is unreliable (M. Bullimore & Bailey, 1995).

Some psycholinguistic factors have also been found to have opposite effects compared to the general population. In normally sighted readers, a large number of orthographic neighbors facilitates word recognition by activating overlapping lexical representations (Coltheart et al., 1977). In contrast, Sauvan et al. (2020) found that larger neighborhood size slows reading in CVL patients, presumably because degraded input makes competing candidates harder to discriminate (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a).

Together, these findings indicate that linguistic properties of text play a crucial role in reading with central vision loss, and that their effect may differ substantially from normal vision, highlighting the need for the present work (Chapter 3 to Chapter 6) to describe them in greater detail. They also underscore the importance of multifactorial models that integrate both visual and psycholinguistic constraints. This gap motivates the current work, which aims to quantify how linguistic predictability, frequency, and orthographic similarity interact with peripheral vision to shape reading efficiency.

2.2.4 Development of PRL

In healthy vision, targets are optimally identified by directing both gaze and attention to the fovea, where spatial resolution is highest. When a central scotoma blocks the fovea, this strategy fails because the target falls within the blind area. Patients must therefore shift their gaze next to the target and focus attention on it - an adaptation known as eccentric fixation (von Noorden & Mackensen, 1962). Over time and with practice, many patients consistently

use a particular area of functioning retina for fixation and detailed visual tasks. This area is called the Preferred Retinal Locus (PRL) (Cummings et al., 1985; Timberlake et al., 1987). Early in the disease, fixation is typically unstable and multiple candidate loci may be used before one becomes an established PRL (Crossland et al., 2005). The chosen location may continue to shift as the disease progresses or as patients practice eccentric viewing.

Although the existence of a PRL is well established, the mechanisms responsible for the specific choice of a PRL are not fully understood. Researchers long believed that patients developed a single PRL. One interpretation, known as the oculomotor re-referencing hypothesis, proposes that the eye movement system recalibrates itself so that the PRL becomes the new reference point, effectively replacing the fovea. In this view, the PRL acts as a “pseudo-fovea” (Cummings et al., 1985; Timberlake et al., 1987; White & Bedell, 1990). A second interpretation, called the attentionally-oriented theory, argues that the visuomotor system is not fully reprogrammed. Instead, patients continue to move their eyes near the target but direct their attention to the healthiest retinal region available (Altpeter et al., 2000; Barraza-Bernal et al., 2017). In this view, the PRL is therefore the preferred attentional locus rather than a fixed reference. A third possibility combines elements of both theories. Many patients, especially early in the disease, alternate between several PRLs, using different loci for different tasks or even switching between them within a single task until one becomes dominant (Crossland et al., 2011; Tarita-Nistor et al., 2023). Crossland et. al described the PRL as “one or more circumscribed regions of functioning retina, repeatedly aligned with a visual target for a specified task, that may also be used for attentional deployment and as the oculomotor reference” (Crossland et al., 2011). To this date, there is still a debate whether multiple PRLs are a step towards an efficient adaptive strategy using a single “best” PRL, or if they constitute the optimal adaptive strategy.

Although a PRL can emerge spontaneously, its efficiency can be improved through training. Training was found to increase fixation stability, reading acuity and reading speed by reinforcing a more advantageous retinal location (S. T. L. Chung, 2011; Maniglia, Pavan, et al., 2016). In addition, reading practice can also reduce the impact of crowding (Levi, 2008); building on this result, one could hypothesize that practice may also reduce the inhibitory impact of some psycholinguistic factors through the establishment of an efficient adaptive strategy, which will be investigated in the present thesis (Chapter 7).

2.2.5 Text simplification

Because adaptive strategies develop with practice, maintaining regular reading habits is critical. Yet many patients abandon reading as their central vision deteriorates, because ordinary text becomes inaccessible. Facilitating access to written text might help patients continue reading on a daily basis, reinforcing their PRL(s) and overall reading performance.

Daily reading practice appears to be a key but under-studied factor in reading with CVL. Sauvan and colleagues showed that AMD patients who continue to read regularly maintain faster reading abilities than those who stopped reading, even when visual acuity is matched (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). The authors

proposed that sustained practice may help preserve oculomotor control, stabilize the PRL, and foster greater reliance on top-down linguistic inference.

One way to encourage such practice is text simplification – the process of reducing the linguistic complexity of a text while preserving its meaning. Originally developed to improve accessibility for individuals with low literacy or language disorders such as dyslexia or aphasia, text simplification can also be applied to low-vision rehabilitation (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrese, 2020). Because the perception of textual difficulty depends on the reader’s abilities and limitations, simplification must be adapted to each target population; readers with low literacy, with dyslexia or with low vision will not necessarily experience the same text features as complex.

From a theoretical standpoint, the psycholinguistic factors described earlier – word frequency, contextual predictability, and orthographic or visual similarity – provide objective ways to modulate text complexity, both at the lexical and semantic levels. Simplifying text along these factors could help compensate, at least partially, for the reduced perceptual span and increased reliance on linguistic inference observed in readers with central visual field loss.

Therefore, prior to developing text simplification guidelines for CVL rehabilitation, the specific text complexities that most affect reading performances in this population need to be identified – a goal addressed in the present dissertation.

By making reading materials more accessible during the early stages of macular degeneration, simplification may not only improve immediate comprehension but also help sustain long-term reading habits, by supporting the adaptive and compensatory mechanisms that enable functional reading in daily life, such as PRL development and oculomotor control.

2.3 Reading with a simulated central scotoma

2.3.1 Advantages of simulated central scotoma paradigms

Using a gaze-contingent simulated scotoma in normally sighted participants offers several advantages for studying reading with central visual field loss. First, the characteristics of the scotoma - its size, shape, and opacity - can be precisely defined and kept constant across participants, eliminating the large inter-individual variability seen in patient populations.

The onset of the scotoma exposure can also be controlled, allowing researchers to examine the very first stages of adaptation and to track compensatory strategies as they develop over time. Eye-tracking is easier and more accurate in simulation. Because calibration is performed with an intact fovea, the eye tracker can be calibrated with normal central vision, ensuring high-quality eye tracking data. Reading performance in normally sighted participants is also more uniform, which reduces variability and makes group data easier to interpret.

Recruitment is simpler, and participants can typically complete longer or more demanding sessions without the fatigue and discomfort experienced by patients.

Taken together, these features make scotoma simulation a powerful tool for investigating reading with central visual field loss and its early stages adaptation.

2.3.2 Experimental evidence

Healthy participants who are asked to read under central scotoma simulation condition rapidly try to compensate by shifting fixation to peripheral retinal locations, developing PRLs or TRL (trained retinal loci). With repeated exposure, training enhances the use of PRLs, improves fixation stability in eccentric regions, and reduces the latency to acquire targets outside the scotoma (Biles et al., 2023; Liu & Kwon, 2016; Maniglia et al., 2020). However, the adaptation process is typically faster and more flexible in simulated paradigms than in patients, who may require months or years to develop stable PRLs (Kwon et al., 2013; Liu & Kwon, 2016).

3 Research question and dissertation overview

Despite extensive research on the visual constraints of reading with central field loss and in healthy eccentric vision, the contribution of psycholinguistic factors remains underexplored. Most clinical and simulation studies have emphasized visual limitations such as crowding, reduced visual span, and fixation instability, while treating the linguistic content of text as a secondary variable. Yet recent evidence suggests that lexical properties of text can have a substantial effect on reading when visual input is degraded. A comprehensive understanding of reading with central vision loss therefore requires an integrated approach that considers both the visual and linguistic determinants of eye-movement control.

The present work addresses this significant gap by measuring the effects of key psycholinguistic variables on reading under central vision loss, both simulated and acquired. Additionally, it aims to identify the adaptive oculomotor strategies that facilitate reading in the absence of central vision. Because reading is central to autonomy and quality of life in this low-vision population, identifying the psycholinguistic determinants of reading difficulty could shape more effective rehabilitation approaches.

Building on this motivation, this dissertation addresses the following central question: **How do visual and psycholinguistic constraints jointly shape reading when central vision is compromised, and what compensatory strategies emerge to sustain reading performance?**

This broad question is examined in the experimental parts of this Thesis (Part II and III) through five main aims:

1. Predictability – Determine whether contextual predictability provides a greater facilitation when foveal input is absent due to the presence of a simulated scotoma (Chapter 3).

2. Orthographic similarity – Compare classical and novel metrics of orthographic neighborhood density to best capture letter-level ambiguity when reading with a simulated scotoma (Chapter 4).
3. Visual ambiguity - Develop and validate two new metrics designed to measure visual ambiguity in words, yield by the presence of letters that share similar features (Chapter 5).
4. Generalization across populations – Test whether these psycholinguistic effects and their interactions with visual factors differ across age groups and between simulated and pathological central field loss (Chapter 6).
5. Adaptive strategies - Characterize the eye-movement patterns and PRLs that allows optimal reading in the absence of central vision, to guide future rehabilitation strategies (Chapter 7).

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1 Participants

All participants were adult native French speakers with no cognitive or reading deficits. They gave written informed consent prior to the experiment. Table 2.1 gives an overview of the different sub-groups tested throughout this thesis.

1.1 Healthy young adults

A total of 57 healthy young adults (age range: 18-32 years, 37 females / 20 males) participated across the different experiments. None reported a history of ophthalmic or neurological disorders, and all had normal or corrected-to-normal vision. Healthy young adults were spread across 4 different testing groups, depending on the visual condition (control vs. scotoma) and reading paradigm (natural vs. self-paced reading) used. Table 1 provides detailed count for each of these groups: control - natural reading (N = 8), scotoma - natural reading (N = 9), control - self-paced reading (N = 13), scotoma - self-paced reading (N = 27). See Chapter 2, Section 4 for details on the different reading paradigms. Healthy young adults were recruited from the various undergraduate programs of Aix-Marseille University. Data from this group of participants will be used in most of the studies presented in this thesis, in Chapter 3, Chapter 4, Chapter 5, Chapter 6 and Chapter 7.

1.2 Healthy older adults

A total of 28 healthy older adults (age range: 61–74 years, 20 females / 8 males) participated across the different experiments. None reported a history of ophthalmic or neurological disorders, and all had normal or corrected-to-normal vision. In addition, participants were tested on the Mini Mental State Examination (MMSE; Folstein et al., 1975) to ensure the absence of early signs of neurocognitive impairment or dementia. Healthy older adults were included in either one of 2 testing groups: control - self-paced reading (N = 8) or scotoma - self-paced reading (N = 20). See Chapter 2, Section 3 for details on the self-paced reading paradigm. Healthy older adults were recruited from Free Time University of Aix-Marseille University. Data from this group of participants will be used in analyses presented in Chapter 6 and Chapter 7.

1.3 Older adults with central vision loss

To be included, participants with central field loss must have had a confirmed diagnosis of age-related macular degeneration or any other maculopathy, an absolute central scotoma in one eye or both and the ability to complete the reading task. Exclusion criteria included cognitive impairment, loss in the peripheral field above the limits of the central scotoma, or total inability in reading the sentences, even at the largest print size. Participants with central vision loss were recruited through the Center of Ophthalmology Monticelli-Paradis or drawn

from existing datasets collected at La Timone Hospital (both in Marseille). Among the hundreds of patients' medical record screened for recruitment at the Center of Ophthalmology Monticelli-Paradis, only 35 patients met the inclusion criteria and were willing to participate. From this pool of recruited patients, only 15 presented with an absolute central scotoma covering the fovea in one eye or both after examination with the microperimeter (cf. Chapter 2 Section 2.3 for details on the visual field examination)¹. Once asked to perform the experimental task, 5 of these 15 patients were not able to read a full sentence and complete the task. Hence, data from only 10 patients met the full list of inclusion criteria (age range: 68-90 years, 3 females / 7 males). To increase our patients pool, data from 38 additional patients were drawn from previous experiments conducted in La Timone Hospital, by colleagues from our research team (Beylerian et al., 2018; Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019) (age range: 47-93 years, 29 female / 9 males). Data from this group of pathological participants were collected towards the end of this PhD and will be used in a study presented in Chapter 6.

For each patient recruited, we collected the following information:

- Name, gender, and age
- Etiology of central vision loss (pathology and localization)
- Lens status of the tested eye (either phakic or pseudophakic)
- Time since diagnosis of central field loss (in years)
- History of low vision rehabilitation
- Past reading habits (for professional purposes and for leisure)
- Current reading habits, including whether patients still read daily and the approximate number of minutes per day
- History of intravitreal injections (ongoing at the time of the experiment or in the past)

¹ All patients recruited from the Center of Ophthalmology Monticelli-Paradis were enrolled quite early after diagnosis in intravitreal injection therapy. As a result, only a minority of them presented with a central scotoma large enough to encompass the fovea.

		Reading paradigm		
		Natural reading	Self-Paced reading	
Healthy young adults				
Visual condition	Control	N = 8 (6F / 2M) Mean age = 19.5 ± 1.4	N = 13 (6F / 7M) Mean age = 24.3 ± 1.8	Reading time ✓ Eye movements ✓
	Simulated scotoma	N = 9 (8F / 1M) Mean age = 21.6 ± 2.6	N = 27 (17F / 10M) Mean age = 23.1 ± 3.1	
Healthy older adults				
Visual condition	Control	---	N = 8 (6F / 2M) Mean age = 68.9 ± 4.3	Reading time ✓ Eye movements ✓
	Simulated scotoma	---	N = 20 (14F / 6M) Mean age = 68.9 ± 3.9	
Older adults with central field loss				
Patients enrolled during this thesis		--	N = 10 (3F / 7M) Mean age = 78.7 ± 6.6	Reading time ✓
Data from previously recruited patients		--	N = 38 (29F / 9M) Mean age = 75.6 ± 11.4	Eye movements ✗

Table 2.1. Summary of all 8 experimental groups and conditions tested throughout this thesis. Data collected with the Self-Paced Reading paradigm in healthy young adults will be used in Chapter 3, Chapter 4, Chapter 5, Chapter 6 and Chapter 7. Data collected with the Self-Paced Reading paradigm in healthy older adults will be analyzed in Chapter 6 and Chapter 7. Data collected with the Self-Paced Reading paradigm in older adults with CVL will be presented in Chapter 6. Data collected with the natural reading paradigm (in healthy young adults) will serve as control to address the potential influence of the Self-Paced Reading paradigm on reading performance and will only be presented in Section 4.3 of the present chapter. In the subgroups highlighted in grey, a few participants will be removed from the different analyses based on their performance, as detailed in Section 6.1.2 of the present chapter.

2 Inclusion tests

2.1 Ocular dominance

All experiments were conducted monocularly. For patients, we selected the eye that matched our inclusion criteria. For healthy participants, we selected their dominant eye. Ocular dominance was evaluated using the Miles test: participants straightened their arm in front of them to create a triangular shape with their thumb and index fingers. With both eyes open, participants target an object in the distance and place it in the middle of the triangle. Then they close their eyes alternately. If the object moves out of the triangle, the open eye is the non-dominant eye. If the object remains in the triangle, the open eye is the dominant one.

2.2 MNREAD

To assess baseline reading performance, we administered a French computerized version of the MNREAD Acuity Charts (Calabrèse et al., 2014). The MNREAD is a standardized test that measures reading speed in relation to print size (Mansfield et al., 1993). Participants read aloud sentences presented monocularly on an iPad, with the text size decreasing

progressively until they could no longer read. Reading speed (words/min) was computed for each print size, and four standard MNREAD parameters were derived: Reading Acuity (RA), Critical Print Size (CPS), Maximum Reading Speed (MRS), and the Reading Accessibility Index (ACC) (Figure 2.1). These measures were used to characterize visual function and verify that participants met the inclusion criteria for the experiments.

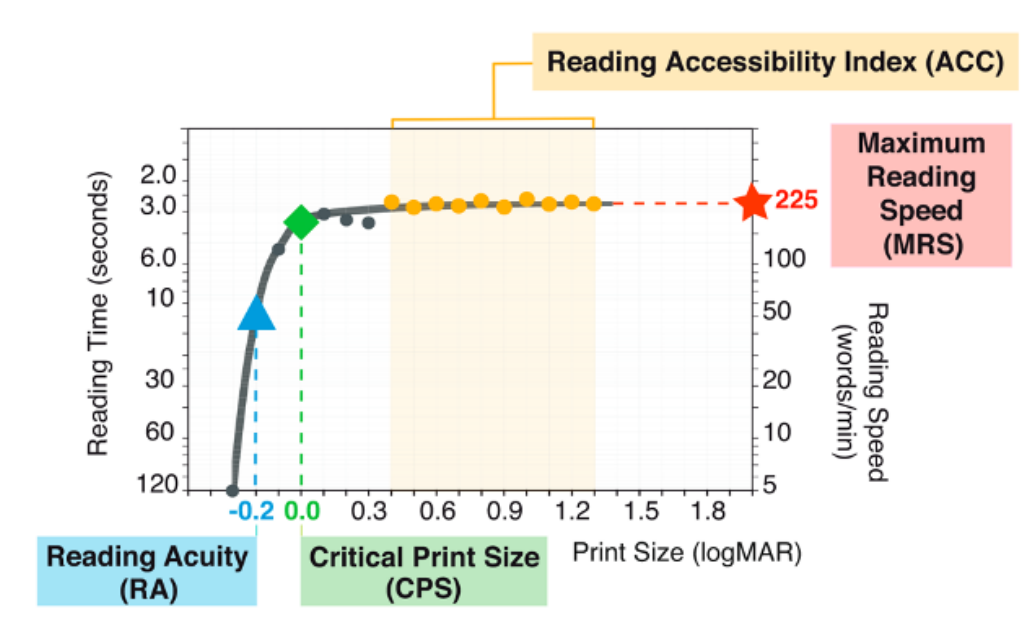


Figure 2.1. The MNREAD chart (left) and a typical MNREAD curve (right). (Calabrèse et al., 2018)

2.3 Microperimetry

To characterize central vision loss and fixation stability, patients completed a fixation exam and a custom microperimetry protocol using the MP-3 microperimeter (Nidek Co., Ltd.). Patients were included only if they exhibited an absolute central scotoma, defined as failure to detect stimuli at one or more locations (even at maximum luminance) in a region encompassing the fovea. Patients with only relative scotomas were excluded. All patients were tested on the microperimeter. Yet, we only got access to the MP-3 data collected in patients enrolled during this thesis (N = 10).

2.3.1 Fixation exam

The fixation test began with participants instructed to fixate a central red cross subtending 1 degree of visual angle. They were asked to find the cross displayed in front of their tested eye and maintain a steady gaze to see it, ideally using their PRL, while the device recorded fixation points in real time via infrared retinal tracking over a 20 second period. Fixation stability was quantified using the Bivariate Contour Ellipse Area (BCEA) method, which estimates the area that encompasses 68% of fixation points (see Figure 2.2). This metric provided an objective

measure of fixation stability for each patient and was used as a covariate in subsequent analyses. No training or repeated sessions were conducted.

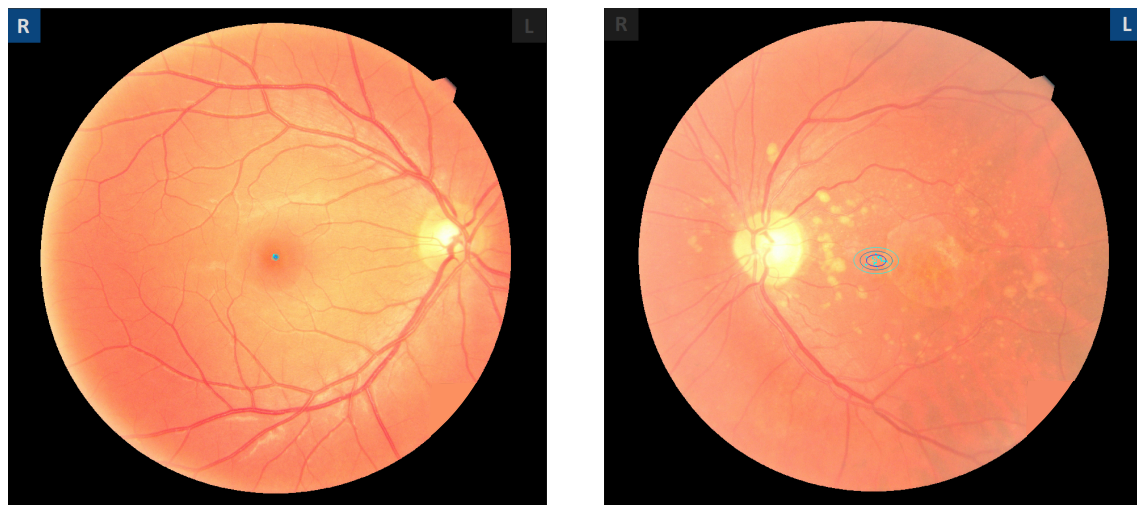


Figure 2.2. Fundus image from a normally sighted left eye (A) and a patient (B), as displayed after the fixation exam. The background image corresponds to a photo of an individual's retina. The red cross is the fixation cross and each blue dot is an eye fixation. The ellipse around the fixations is the 68% BCEA.

2.3.2 Microperimetry exam

Following the fixation exam, participants completed a custom microperimetry protocol designed to map central scotomas with high resolution. See Figure 2.3 for the custom pattern. During the exam, participants fixated a larger red cross (4 degrees of visual angle), again ideally using their PRL, while responding to brief light stimuli presented at various retinal locations.

A custom stimulus grid consisting of 29 locations was created to densely sample the region immediately surrounding fixation. More stimuli were concentrated near the center to allow for fine mapping of central vision, where scotomas were expected to be most prominent. Stimuli were of Goldmann size V, presented on a 10 candela/meter² (cd/m²) background, and delivered using a 4-2 staircase strategy to measure sensitivity thresholds. The MP3's dynamic range extended from 0 dB up to 34 dB – with 0 dB corresponding to the brightest stimulus (approximately 3200 cd/m²), and 34 dB corresponding to the dimmest (approximately 11 cd/m²).

Participants were instructed to press a response button each time they perceived a stimulus flash. Locations where the participant failed to detect stimuli at the maximum luminance level were classified as absolute scotoma points. Patients who detected all 29 locations were classified as having at most a relative central scotoma and were not included.

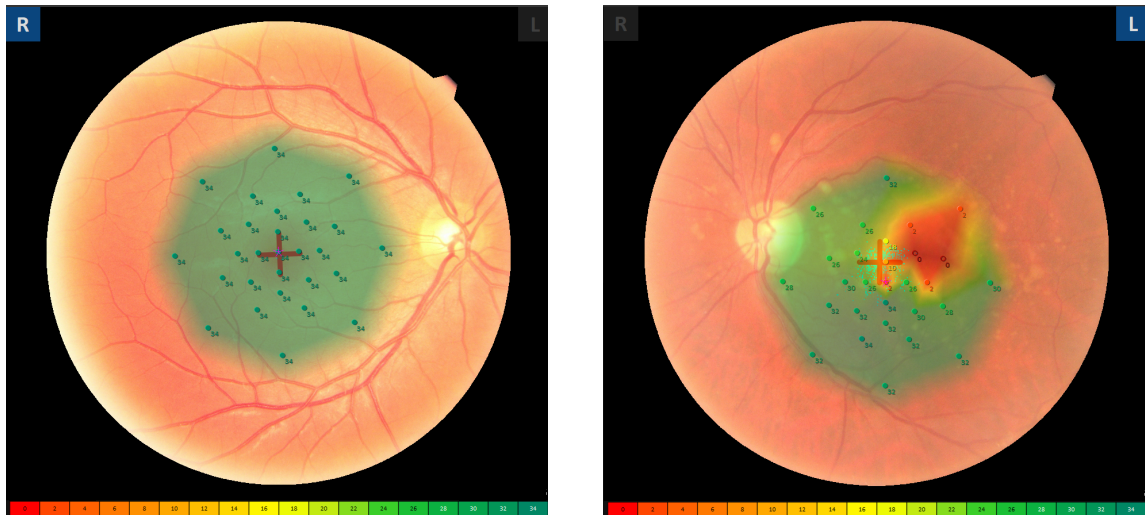


Figure 2.3 Microperimetry exam images from a healthy individual (A) and an individual with CVL (B). The red cross in the center spans 4 degree of visual angle and serves as the fixation target. Light blue dots represent recorded fixation points during the task. The green circles represent the pattern of stimuli all around the red cross, with their corresponding sensitivity values, indicated by the highest attenuation level (in dB) at which each stimulus was detected. Green means that the stimuli was always perceived and red means that the stimuli was never perceived, even at its brightest display. This custom pattern was designed with higher density of stimuli near the fixation cross to enable fine mapping of central vision loss, while fewer stimuli were placed in the periphery. All stimuli are confined within a diameter of 20 degrees of visual angle.

3 Experimental setup

Reading experiments were completed using one of three setups, based on the participants' visual status: an eye-tracking setup – with or without scotoma simulation (for healthy readers); a simple screen setup or a virtual reality setup (for patients with central field loss).

3.1 Healthy participants

3.1.1 Eye tracking setup

Apparatus

This setup was composed of an EyeLink 1000 system with the Tower Mount configuration, which provides the largest field of view among all mounting systems for this high-speed camera. The system was paired with a 21-inch CRT monitor with a refresh rate of 120 Hz using the PsychoPy library (Peirce, 2007, 2009). At a viewing distance of 40 cm, the display area of the monitor was 56 x 42 deg (1152 x 864 pixels) (Figure 2.4).

The EyeLink 1000 tracks the eye using infrared illumination and high-speed video capture (1000 Hz), detecting the pupil and the corneal reflection to estimate gaze position with high spatial and temporal accuracy. In the Tower Mount configuration, an infrared illuminator and the high-speed camera are mounted above the participant's head, aimed down toward a

semi-transparent mirror set at a 45° angle in front of the screen. This mirror reflects the infrared light from the eye back into the camera while remaining transparent to visible light, so the participant can see the stimulus display normally. A standard 9-point calibration procedure was performed at the beginning of each block of reading, followed by a drift check on every trial. The chin and forehead rest ensured head stability, minimizing movement and maintaining calibration accuracy.

This configuration allowed us to estimate fixations and saccades characteristics reliably during reading. For each word, we collected the number of fixations and their durations as key oculomotor outcome measures.

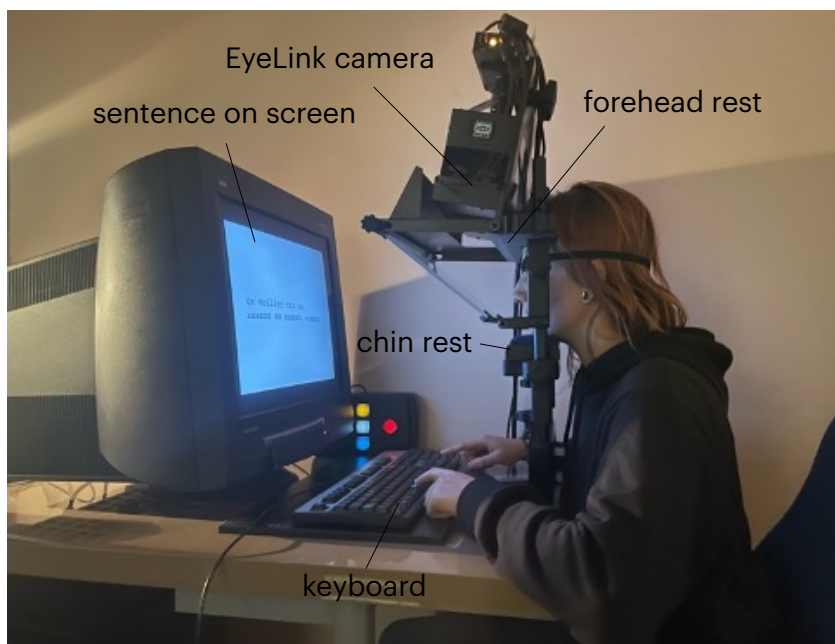


Figure 2.4. Experimental setup using eye-tracking. The participant is seated in front of a screen and uses a keyboard to display words at their own pace. Her head is stabilized using both a chin rest and a forehead rest to ensure proper positioning.

Scotoma simulation

In order to simulate central field loss, we used real-time eye tracking to display a 10° diameter mask centered on gaze, referred to as a gaze-contingent central scotoma. We chose 10° because this size overlaps the foveal region ($\approx 5^\circ$) and extends into the central macula ($\approx 17^\circ$ in diameter), thereby representing a moderate lesion size that disrupts fine-detail foveal vision while still allowing potential use of peripheral strategies. Comparable scotoma sizes have been used in previous gaze-contingent reading studies (J.-B. Bernard et al., 2007; Kwon et al., 2013; Walsh & Liu, 2014). The simulated scotoma was circular and filled with a dynamic noise texture composed of randomly scattered black and white pixels, designed to maintain perceptual disruption. The mask dynamically followed the participant's gaze and was updated at a refresh rate of 120 Hz, ensuring smooth and continuous masking of central vision during reading.

Stimuli

Stimuli were created with the PsychoPy library (Peirce, 2007, 2009). Characters were black (0 cd/m²) on a grey background (32 cd/m²), displayed in Courier font. Sentences were left justified, vertically centered on the screen and displayed over 2 to 4 lines depending on their

length. Based on previous measurements of CPS in peripheral vision (S. T. Chung et al., 1998, 2004), we chose an optimal letter size of 1.3°. This print size was adopted because it allowed to fit long sentences on the screen while subtending approximately twice the CPS for normal vision at 5° in eccentricity and once the CPS at 10°.

3.2 Patients with central field loss

3.2.1 Computer setup

Apparatus

Within this simpler setup, the task was conducted without an eye-tracker. Stimuli were displayed on an LCD HP LE2201W monitor with a 60 Hz screen refresh rate. Within the full display area of this monitor (47.4 × 29.6 cm; 1680 × 1050 pixels), a 1400 × 1050 pixel window was used to display our stimuli. At the viewing distance of 40 cm, this window subtended 56° × 42°.

Stimuli

Stimuli were created with the PsychoPy library (Peirce, 2007, 2009). Characters were black (0 cd/m²) on a grey background (32 cd/m²), displayed in Courier font. Sentences were left justified, vertically centered on the screen and displayed over 2 to 4 lines depending on their length. Print size was chosen optimally for each participant as the value of his/her Critical Print Size, measured before testing with the MNREAD test.

3.2.2 Virtual reality setup

A virtual reality (VR) version of the experiment was also developed to run experiments on CVL patients requiring very large print. Indeed, the VR setup allowed the presentation of much larger letter sizes than were possible on a traditional monitor. For instance, standard screen displays supported a maximum letter height of approximately 1.3 logMAR, whereas the VR system enabled presentation sizes up to 3.0 logMAR. In addition to the increased visual scalability, the VR setup was highly portable, making it easy to conduct sessions directly within the ophthalmology clinic without the need for bulky equipment.

Apparatus

We used the VR headset called HTC Vive Pro Eye head-mounted display (HMD). The nominal size of the field of view of the HMD was 110°. Participants held one controller in each hand, to display the previous (left hand) or next word (right hand - Figure 2.5). The headset and controllers were tracked by two base stations located on both sides of the participant. The experiment took place monocularly, the other lens of the headset displaying a black screen.

Stimuli

Stimuli were created using the Perception Toolbox for Virtual Reality (PTVR; Castet et al., 2024). As described in Section 1.3.1, characters were black (rgb(0,0,0)) on a grey background (rgb(0.5,0.5,0.5)), displayed in Courier font. Sentences were left justified, vertically centered on the screen and displayed over 2 to 4 lines depending on their length, at the participant's eye level. Print size was chosen optimally for each participant as the value of their Critical Print Size, measured before testing with the MNREAD test.

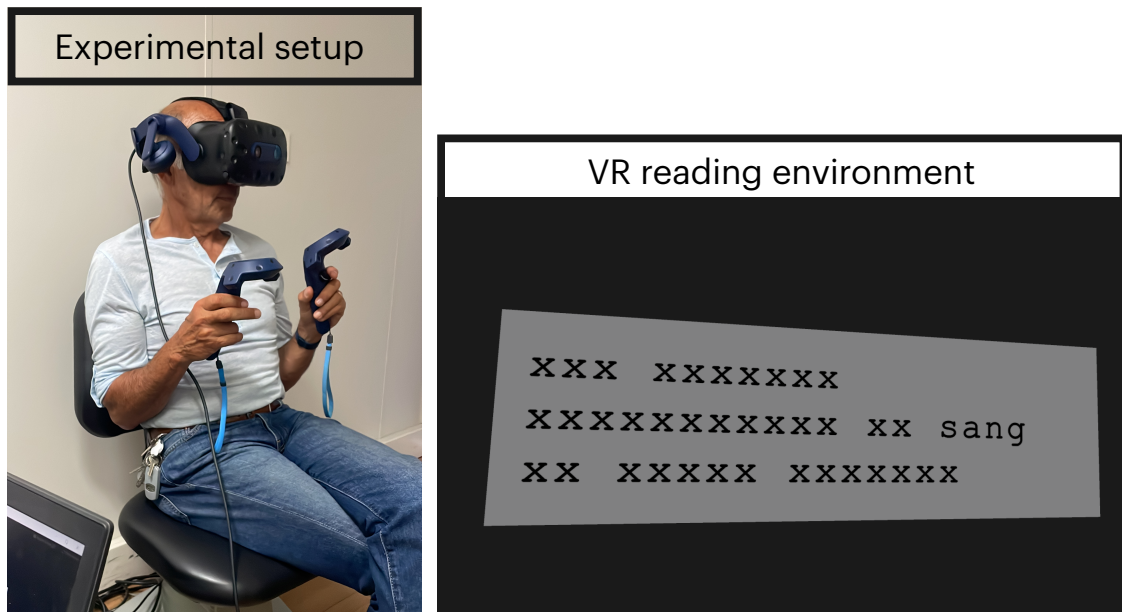


Figure 2.5. Experimental setup for patients who read sentences in Monticelli center, using a VR headset. (A) is the participant wearing the VR headset during the reading task and (B) is an example of sentence displayed in the VR headset.

4 Experimental paradigm

All experiments in this thesis involved reading simple French sentences using either our main reading paradigm: the self-paced reading (SPR), or a “natural reading” paradigm.

4.1 Self-paced reading (SPR) paradigm

In normally sighted readers, one can estimate word reading time by identifying and summing fixations that land on a given word. However, in the case of central vision loss, fixations tend to scatter across the sentence, making it difficult or impossible to attribute fixations to individual words with confidence. Hence, word-by-word reading time is extremely difficult to estimate with standard eye-tracking methods in the presence of a central scotoma

(simulated or acquired). The self-paced reading (SPR) paradigm (Just et al., 1982) overcomes this limitation by isolating each word in time, using a word-by-word moving window.

In each trial, a sentence was displayed in front of the participant, with only one word visible at a time – the others being hidden by strings of x’s (see Figure 2.6). Participants were instructed to read aloud as quickly and accurately as possible once the sentence appeared. Participants advanced through the sentence by pressing a response key (either on a keyboard; or on a controller in VR), which triggered the revealing of the next word while masking the previous one. They could also press a second key to go back and display the previous word again. This format mimics natural reading by enabling eye movements, while allowing the measurement of reading time (RT) for each word — defined as the time a word was displayed. In cases where a word was read multiple times, word RT was calculated as the sum of all reading passes. The experimenter monitored the accuracy of each word as well as the comprehension of the sentences.

4.2 Natural reading paradigm

Despite its obvious perks for studying reading with a scotoma, the SPR still presents a strong limitation by slowing down one’s natural reading pace. Indeed, words must be read sequentially, with the addition of a manual motor task, imposing a time constraint on reading speed. While this constrain is negligible when individuals have to read with eccentric vision, it becomes strong enough without a scotoma to slow down the reading process. In order to estimate the impact of the SPR reading paradigm on reading speed alone, a subset of participants was asked to read short sentences displayed using an ecological layout, with all words visible at all times. Apart from that, font, print size and overall sentence display were identical to the SPR (Figure 2.6).

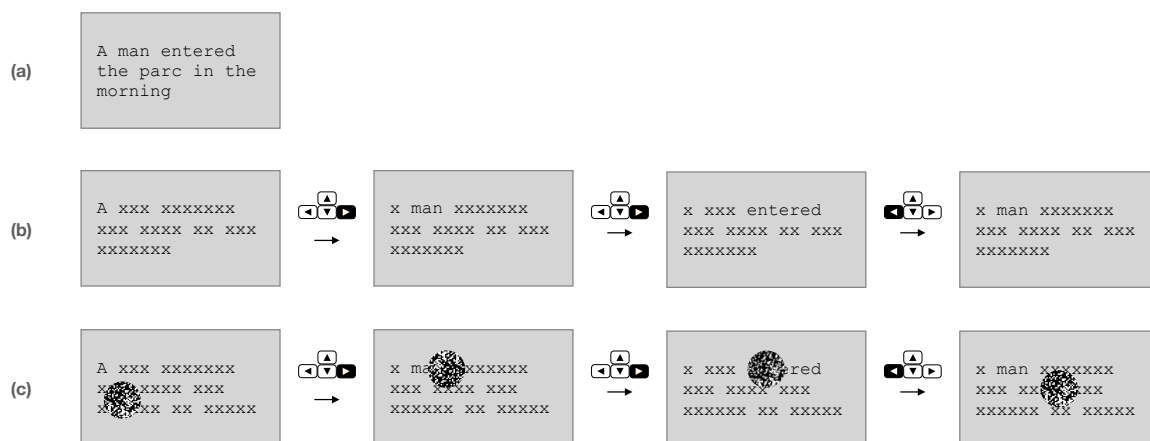


Figure 2.6. Experimental design of the natural reading paradigm (a), the self-paced reading paradigm (b), and the SPR paradigm with a simulated central scotoma, mimicking central vision loss (c). In the natural reading paradigm, participants saw the full sentence and read it aloud. In the SPR paradigm, words were revealed one by one, forward or backward, at the participant’s pace. In all cases, the experimenter ended the trial when all words were pronounced.

4.3 Addressing the difference between SPR and natural reading

To estimate the overall impact of SPR on reading performance and dissociate it with any potential influence of the simulated scotoma we will discuss in subsequent chapters, we compared the same sentences read either with the self-paced reading paradigm (SPR, i.e. sequential word presentation) or with a natural reading condition (noSPR). Data presented in this section were collected in healthy young adults, using the natural reading paradigm (N = 9 with a simulated scotoma; N = 8 without a simulated scotoma) and using the self-paced reading paradigm (N = 27 with a simulated scotoma; N = 13 without a simulated scotoma), as described in Table 2.1.

4.3.1 Influence of SPR on reading time

Across groups, reading time was systematically longer with SPR compared with natural reading. On average, sentences were read 30% slower (SD = 10%) with SPR than in noSPR for control readers, and 14% slower (SD = 27%) for simulated scotoma readers. The effect was therefore larger and more consistent in controls, while more variable in the scotoma group.

Figure 2.7 shows that in the control group reading with central vision, nearly all sentences are read faster with natural reading, indicating that sequential reading systematically slowed down reading. In the simulated scotoma group, reading time was also generally faster in natural reading, but there was also a subset of sentences that were read faster with SPR, showing that the paradigm did not always penalize performance in eccentric viewing.

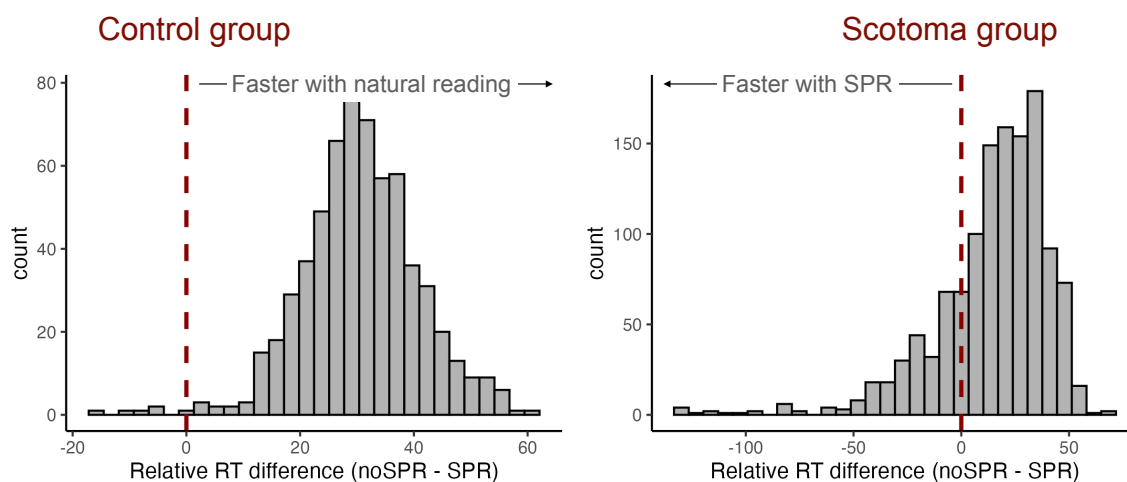


Figure 2.7. Histogram of the relative difference in reading time (RT) between paradigms (noSPR – SPR), expressed as a percentage. Positive values indicate faster reading in natural reading (noSPR) and negative values indicate faster reading in SPR. Each count on the y-axis represents the number of sentences falling into a given bin of relative RT difference (608 sentences in total). The left panel shows control readers, and the right panel shows simulated scotoma readers. A vertical dashed line at 0 marks the point of no difference.

4.3.2 Influence of SPR on reading time across blocks

To better understand these patterns, we examined the evolution of reading time with both paradigms across blocks (Figure 2.8). In the control group, SPR was consistently slower than natural reading throughout the experiment, with the gap persisting across practice. In the scotoma group, SPR slightly facilitated performance in the earliest blocks, likely because displaying one word at a time provided a temporary visual guide and reduced crowding, which is particularly disruptive when readers are first confronted with a central mask forcing them to use eccentric vision. As readers adapted and became more efficient at processing sentences in eccentric vision, this facilitation disappeared, and SPR became consistently slower than natural reading. The guiding effect of SPR at the beginning of training may have accelerated the initial stages of adaptation.

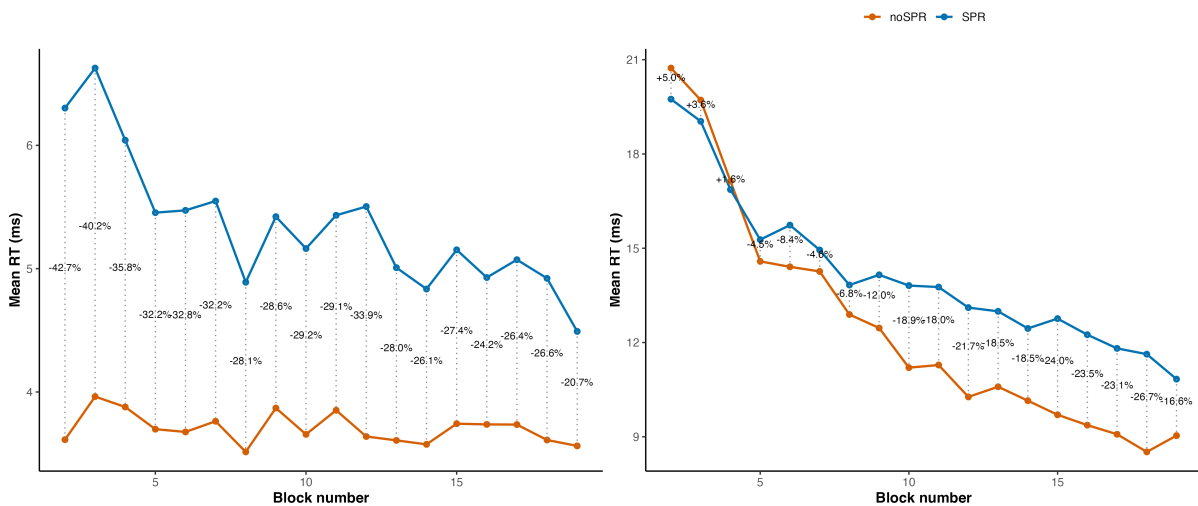


Figure 2.8. Mean sentence reading time (RT) as a function of block number, shown separately for natural reading (noSPR, red) and sequential reading (SPR, blue). Points represent mean reading time per block and are connected by lines; percentages indicate within-block differences between paradigms. The left panel shows control readers, and the right panel shows simulated scotoma readers. Note that the y-axis scale is very different across both groups.

5 Linguistic material

Data acquired and analyzed during this thesis were obtained using two different corpora of sentences previously created in our lab. First, we will present each of these corpora, then we will describe new linguistic measures derived for each word to better characterize them.

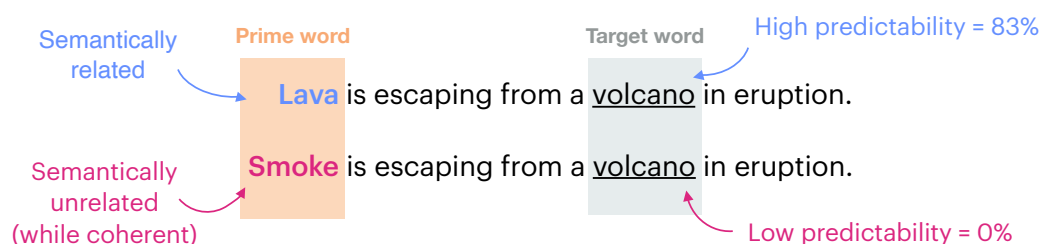
5.1 Reading corpora

5.1.1 Corpus #1

The French Sentence Corpus (608 sentences) was previously designed by members of our lab, to investigate eye movements during typical reading (Albregues et al., 2019). Sentences

were constructed as pairs, each pair differing only by a prime word (in position 2–3). The prime rendered a later target (mean lag = 3.8 words) either predictable or unpredictable while holding syntax constant. Predictability was measured with a cloze task on a separate participant sample, yielding two scores per target (respectively associated to the related vs unrelated prime). Predictable targets were guessed by 22–100% of respondents ($M = 0.67$, $SD = 0.23$), unpredictable by 0–4% ($M = 0.005$, $SD = 0.013$). Sentences were 31–69 characters ($M = 50.6$, $SD = 7.3$) and 6–14 words ($M = 9.0$, $SD = 1.4$). Each participant read one sentence per pair; lists were counterbalanced to maintain a 50/50 split of predictable/unpredictable items (Figure 2.9).

(a) **Predictable vs. unpredictable sentence pairs** ($n = 304$)



(b) **Creation of two sentence sets containing one sentence from each pair**



Figure 2.9. Construction steps of Corpus #1. (a) Within a pair, sentences were composed of identical word sequences differing by only one word (the prime word), which was either semantically related to the target (predictable condition) or semantically unrelated to the target (unpredictable condition). (b) From the 304 pairs of sentences, two different sets were created, containing one or the other sentence from each pair, with an equal number of predictable and unpredictable sentences.

5.1.2 Corpus #2

This corpus (80 sentences) was created previously in our lab for different studies (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019). As in corpus #1, sentences were constructed as pairs, each pair being identical except for a single target word (Figure 2.10). Within each pair, the two unmatching target words were interchangeable synonyms with the same number of characters but different values of

frequency and a different number of orthographic neighbors (N). Sentences were 31–69 characters (M = 55.9, SD = 5.6) and 6–14 words (M = 10.1, SD = 1.4). Each participant read one sentence per pair.

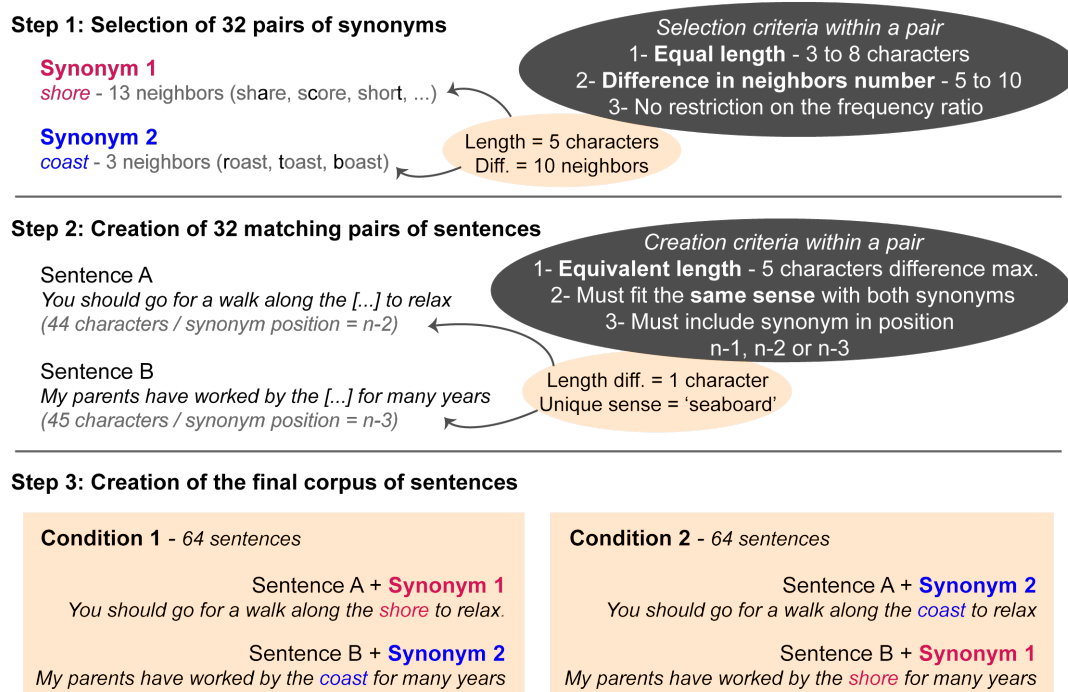


Figure 2.10. Construction steps of Corpus #2. Extracted from Sauvan et al., 2020.

5.1.3 Lexical vs grammatical words

To focus on semantically rich items of reading while still studying a more ecological dataset: Analyses were limited to lexical (content) words, including nouns, verbs, adjectives and adverbs, based on TreeTagger's online French part-of-speech tagging (Schmid, 1994). These words carry semantic content and are more relevant to studying lexical access and contextual integration. In contrast, grammatical (function) words – such as articles, pronouns, prepositions, and conjunctions – primarily encode syntactic structure and offer limited semantic information. Including them would likely increase noise in models focusing on semantic and lexical effects and dilute the statistical power to detect effects of interest (Schmauder et al., 2000).

5.2 Psycholinguistic measures

Psycholinguistic measures can be used to assess lexical difficulty and orthographic competition, known to influence both behavioral reading measures and eye movements in normal reading and reading with CVL (Chapter 1). In the present work, each word of the corpora presented above was characterized with several psycholinguistic variables. These

variables were used as predictors in the statistical models to investigate how word-level properties influence reading behavior. Below, we describe each of these psycholinguistic measures.

5.2.1 Length

Word length corresponds to the number of characters within a word. For each word of our corpuses, word length was extracted from the Lexique 3.83 database (New, 2006).

5.2.2 Frequency

Word frequency refers to how often a word occurs in the language. For each word of our corpuses, word frequency was estimated as the frequency of the lemma (base form of the word), in occurrences per million from movie subtitles. Word frequency was extracted from the Lexique 3.83 database (New, 2006).

5.2.3 Number of orthographic neighbors (N)

Coltheart's N refers to the size of a word's orthographic neighborhood (i.e., its number of neighbors) by measuring how many words can be produced by changing a single letter while preserving letter positions and length (Coltheart et al., 1977). For each word of our corpuses, N was extracted from the Lexique 3.83 database (New, 2006).

5.2.4 Orthographic Levenshtein Distance (OLD20)

The Orthographic Levenshtein Distance 20 (OLD20) calculates the average number of single-letter edits (insertions, deletions, and/or substitutions) needed to change a word into its 20 closest neighbors (Yarkoni et al., 2008). It was design to considering a broader range of similar words (including those of different lengths) than the more restrictive measure of orthographic similarity, N. Smaller OLD20 values indicate denser orthographic neighborhoods, while larger values signal sparser neighborhoods. For each word of our corpuses, OLD20 was extracted from the Lexique 3.83 database (New, 2006).

5.2.5 In-context predictability

Word predictability captures how well a word fits the preceding sentence context. Therefore, it is not intrinsically related to a word itself, and must be estimated for each word in a specific sentence.

As mentioned above, Corpus #1 was originally designed to focus on the prime-target dynamics and provided a measure of in-context predictability for target words only. This measure of predictability, limited to a single word from each sentence from Corpus #1, was sufficient for the purpose of Study 1 (Chapter 3). However, starting from Study 2 (Chapter 4),

the present dissertation adopted a broader approach by analyzing most words in each sentence. This methodological choice was motivated by several reasons:

- Reading time and eye movement measures being available for every word in the sentence, including all words allowed for richer datasets, enabling more powerful statistical analyses.
- Limiting the analysis to target words, that were specifically chosen to drive very low and very high scores of predictability, could artificially inflate the effect of predictability. By including all words, we account for the contribution of a wider range of lexical and contextual variables, and we erase the predominance of predictability as a single explanatory factor.

This methodological choice required us to estimate in-context predictability for all words of both Corpus #1 and Corpus #2. For practical reasons, this was done in two different ways: either by running a side experiment using a cumulative cloze task on healthy readers (human-estimated predictability; Corpus #1) or by generating predictability scores with a recent AI language model (AI-generated predictability; Corpus #2).

A. Human-estimated predictability (Corpus #1)

Predictability scores for each word in the sentences from the French Sentence Corpus were collected in a separate study conducted in our research group ². This method, inspired by earlier work on incremental predictability (Luke & Christianson, 2016) reflects how contextual constraint builds up across the sentence during natural reading.

Estimation of the cumulative cloze task measure - Each sentence was presented one word at a time to 105 French participants (Figure 2.11). After viewing the current word, participants were asked to guess and write down the next word. Once they answered, the actual word was revealed, and they were asked the same question again. This procedure continued until the end of the sentence. Non-responses were discarded. A predictability score was calculated for each word based on the percentage of participants who guessed it correctly. These scores were normalized to range from 0 to 1 (corresponding to the percentage of correct answers) and used as a continuous predictor in our statistical models of reading behavior. This approach allowed us to model in-context predictability as a continuous variable for all words.

² Predictability norms were collected for other research purposes by Françoise Vitu in collaboration with Aurélie Calabrèse, Laure Spieser and Régis Mancini

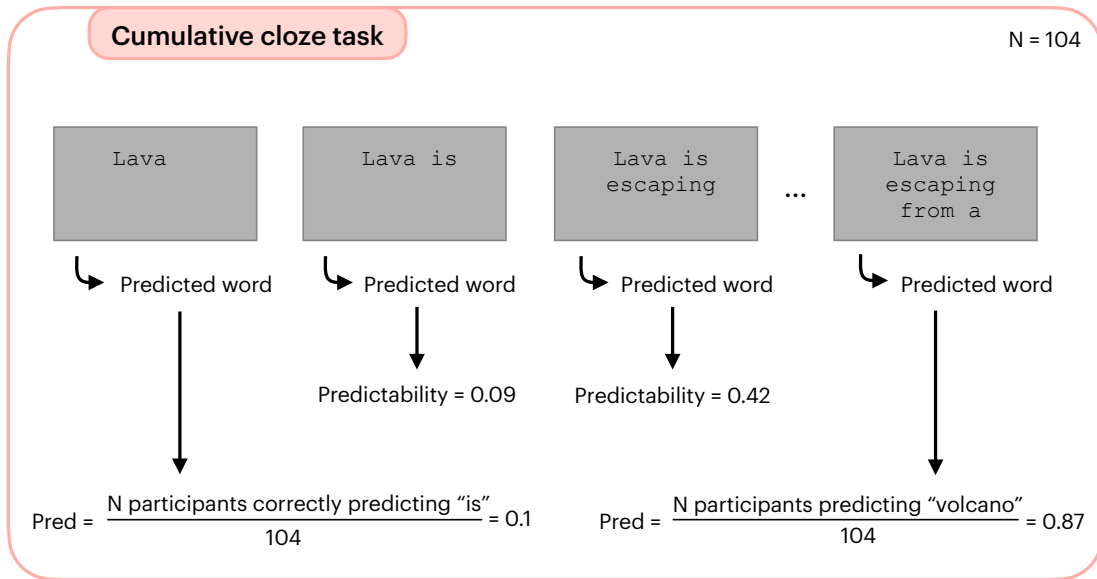


Figure 2.11. Step-by-step illustration of the measure of in-context predictability using a cumulative cloze task. This procedure was applied to all 608 sentences in the corpus.

Validation of the cumulative cloze task measure - To validate the cumulative cloze measure, we compared it to the original target-word predictability scores reported by (Albregues et al., 2019). Since the original cloze procedure was limited to target words, we restricted the comparison to this subset. A Spearman correlation was computed between the two sets of scores, yielding a very strong relationship ($R = 0.91$ - Figure 2.12). This result demonstrates that the word-by-word cumulative cloze task procedure produces predictability estimates highly consistent with the original cloze task, while additionally extending predictability measures to all words in the sentence.

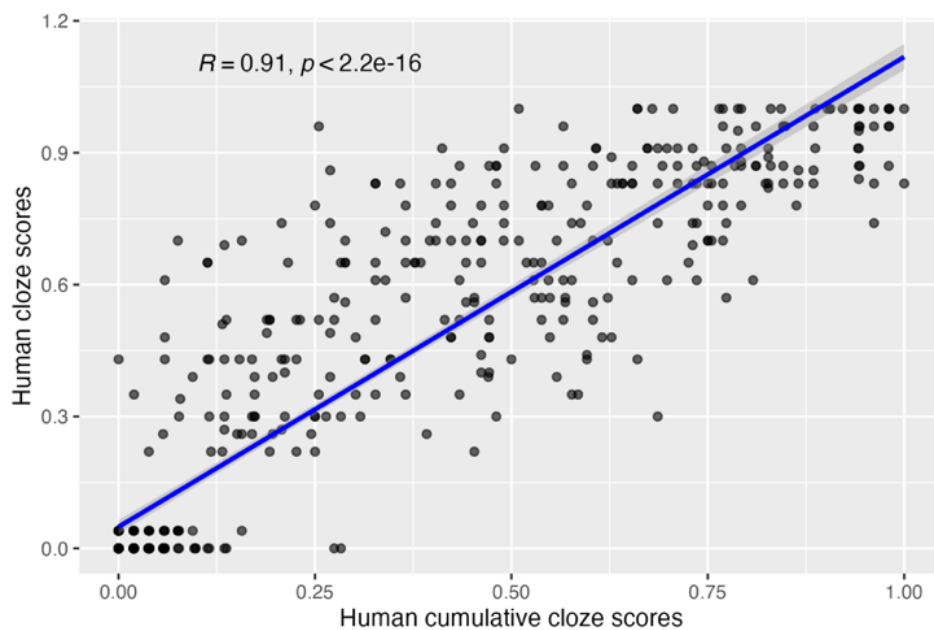


Figure 2.12 Correlation between original target-word cloze scores (Albregues et al., 2019) and cumulative cloze scores from the left-to-right procedure ($R = 0.91$).

B. AI-generated predictability (Corpus #2)

As opposed to Corpus #1, no human cloze predictability data were available for Corpus #2. Because such dataset requires to run time-consuming experiments on a very large number of participants, we decided to estimate the in-context predictability of each word from Corpus #2 using Large Language Models.

We chose *CamemBERT* (Martin et al., 2020) to perform this task. CamemBERT is a transformer-based language model pretrained on large French corpora and built on BERT architecture (Devlin et al., 2019). It is trained on OSCAR, French Wikipedia, and other large-scale French sources, making it more suitable for the present study than multilingual or English-trained models. This choice was motivated by prior work showing that transformer-based surprisal estimates (e.g. from BERT-type models and GPT-2) are among the strongest computational predictors of human reading times, and specifically using the SPR paradigm (Merkx & Frank, 2021).

Use of BERT with a left-context restriction - BERT models are trained with a masked language-modeling training procedure: a randomly selected word in a sentence is replaced by a mask token, and the model learns to predict it from its surrounding context. To align the predictability measure more closely with human reading, and with the cumulative cloze task, we adapted the procedure to rely on left context only. For each target word in a sentence, only the preceding words were provided to the model, with the target replaced by a mask. For example, in the sentence *The penguin walks on ice*, the word *walks* was predicted from *The penguin <mask>*, and *on* was predicted from *The penguin walks <mask>*, and so on. This restriction ensures that predictions are based only on the linguistic information available up to that point, mirroring the incremental nature of human reading.

Computation of the camemBERT predictability measure - Predictability scores were computed in Python 3.11.13 using the transformers, torch, pandas and numpy packages. The transformers package (Hugging Face) provided access to the pretrained CamemBERT model through the classes CamembertTokenizer and CamembertForMaskedLM, and to a ready-to-use prediction tool via the function pipeline.

Validation of the camemBERT predictability measure - To assess validity of this computational measure of predictability, we also computed camemBERT-based scores for Corpus #1 and compared them to the cumulative cloze scores. For each word from Corpus #1, we computed a left-context CamemBERT score and correlated it with the available human values (Figure 2.13; left panel). The Spearman's correlation reached 72%, indicating substantial agreement between the two measures. Given this level of correspondence, we considered the CamemBERT-based measure sufficiently accurate to be applied to our own corpus.

Comparison with alternative language models - We also tested other pretrained language models for French. FlauBERT, another BERT-type model trained on French text, showed lower correspondence with human cloze scores. GPT-2, a unidirectional generative model not specifically trained on French, reached a moderate correlation of 0.63 (Figure 2.13; right panel). However, neither model outperformed CamemBERT, which we therefore selected.

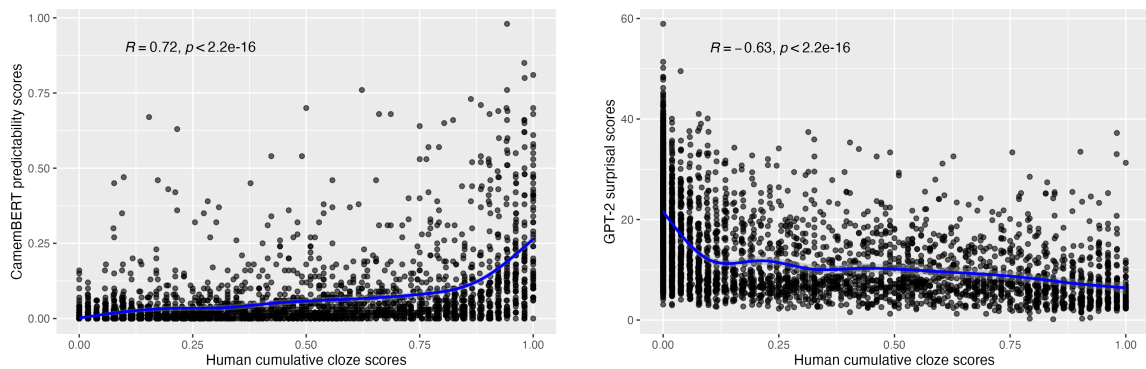


Figure 2.13. Correlation plots between the human cumulative cloze scores collected by Aurélie Calabrèse and Françoise Vitu, and 2 other predictability scores: (left) Correlation of 0.72 with the camemBERT predictability scores, on all words of the corpus. (right) Correlation of -0.63 with the GPT-2 surprisal scores, on all words of the corpus.

5.2.6 Maximum neighborhood frequency

Beyond orthographic neighborhood size (e.g., Coltheart’s N), the maximum neighborhood frequency was computed for each word. While some studies use the mean frequency of orthographic neighbors to capture distributed lexical activation (i.e. in naming tasks), we opted for the maximum frequency to better capture potential lexical inhibition effects relevant for fast reading.

This measure reflects the frequency of the most frequent orthographic neighbor of a given word, which may exert the strongest lexical competition during word recognition (Grainger & Jacobs, 1996). The latter measure captures potential effects of lexical competition and similarity-based interference. A highly frequent neighbor could interfere with word recognition due to increased activation of competing lexical candidates. Thus, maximum neighborhood frequency served as a useful index of potential lexical interference under these challenging reading conditions. The maximum neighborhood frequency was measured from two different measure of orthographic similarity: Coltheart’s N and OLD20.

Figure 2.14 illustrates how the maximum neighborhood frequency (maxNF) was computed for both Coltheart’s N and Yarkoni’s OLD20. In the green frame are the 7 strict neighbors of the word “eye”. The most frequent neighbor is “bye”, so the max NF for “eye” is 180.1 per-million when we compute max NF for Coltheart’s N. And the most frequent neighbor is “eyes” when we take into account OLD20 neighbors, with a max NF of 221.5 per-million.

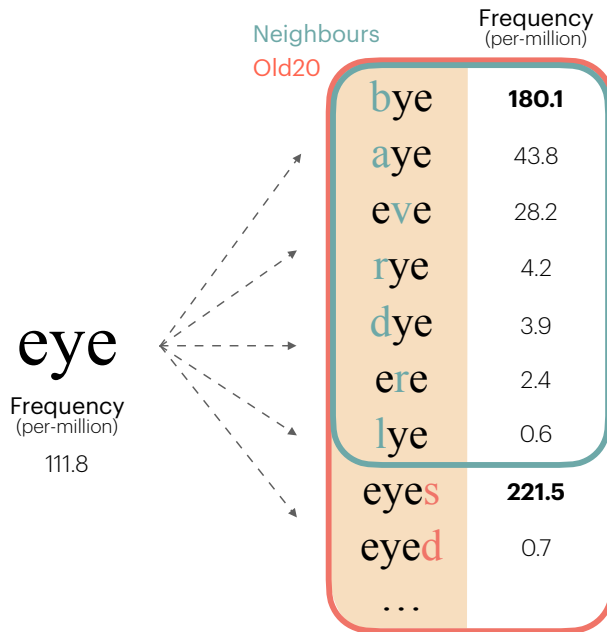


Figure 2.14. Illustration of how maximum neighborhood frequency (max NF) was computed for both Coltheart's neighbors and for Yarkoni's OLD20.

6 Data processing

6.1 Reading performance data

6.1.1 Accuracy

Accuracy was coded live by the experimenter during the reading task. The experimenter had the target sentence displayed and verified that each word pronounced matched the intended word. A word was considered inaccurate if another word was produced in its place. Error rates were minimal and are reported in the corresponding studies.

6.1.2 Reading time

Only correctly read words were included in the statistical analyses of reading time. Reading time (RT) was computed at the word level and, in self-paced reading (SPR) experiments, corresponded to the total duration during which a word was displayed on screen. This encompassed both fixations and saccades. RT was defined as the interval between the appearance of a word on a screen, up until the reader moved on to the next word.

Words for which RT was equal to 0 seconds or greater than 20 seconds were excluded from the analysis. Technical errors and incorrectly read words were also excluded, as described in the previous section. RTs were expressed in seconds and log-transformed to better approximate a normal distribution prior to statistical modelling.

Only words read in a single forward pass were retained. Words that were revisited during subsequent passes represented a negligible proportion of the data and were excluded to ensure comparability across participants and conditions. For the few control participants

who read the sentences naturally (i.e. without SPR), the same computation was applied at the sentence level, corresponding to the duration between sentence onset and offset.

Choice of measure: gaze duration vs total viewing time. We also considered whether using gaze duration (i.e. excluding saccades) instead of total viewing time would change the results. In controls, where saccades are short and precise, both measures yielded very similar outcomes. However, under simulated scotoma, participants produced 2.2 to 4.4 more fixation per word, which also implied a substantial increase in the number of saccades. If only gaze duration were considered, these additional saccades—and the processing that continues during them—would be excluded, leading to an underestimation of reading time. Total viewing time, in contrast, integrates processing across multiple fixations and the intervening saccades, providing a more accurate estimate of the continuous nature of reading. This justifies our choice to use total viewing time, particularly given the atypical oculomotor behavior induced by CVL.

Plotting individual learning profiles to select participants

A key methodological concern in this study was determining whether participants reading with a simulated central scotoma reached a performance plateau within the experimental timeframe, or whether they were still improving by the end of the experimental sessions. This was particularly important to understand whether the approximately 4 hours of reading with a simulated central scotoma provided sufficient opportunity for adaptation and strategy development in eccentric viewing. The main goal of this analysis was to identify learning thresholds. This allowed us to optimize data selection in two different ways: (1) by excluding participants who did not reach a stable performance plateau in each subsequent analysis, and (2) by restricting the analyses to plateau blocks only, i.e., experimental segments where performance was stable (Figure 2.15).

To address this, we computed a learning curve for each participant who read with the simulated scotoma. Learning curves are graphical representations illustrating how participants adapted to a simulated central scotoma, and thus how reading performances improved with practice over time – it plots the average reading time as a function of block number. For each participant, we computed the mean reading time per block (i.e., 16 sentences), along with its standard deviation. The analysis was restricted to correctly read words from trials without technical or behavioral issues and excluded words with extreme reading times over 20 seconds.

For each curve, we used an MNREAD-inspired plateau detection. As described by the MNREAD plateau algorithm (Mansfield et al., 1996), we first determined a statistical plateau for which all reading speeds measured outside of it was at least 1.65 standard deviations slower than the average speed on the plateau (representing a confidence level of 95% with a one-tail distribution). The last point on the plateau was considered a breakpoint and used as a starting point for fitting a piecewise linear regression model in R using the Segmented package. The first slope (before the breakpoint) showed early improvement, while the second part of the slope (after the breakpoint) indicated whether performance stabilized. The flatter

the second slope, the more stable the plateau. Learning curves of representative subjects are presented in Figure 2.15.

A participant was considered to have reached a plateau if:

- The plateau covered 25% to 85% of the total experiment duration;
- The first slope showed clear improvement at the beginning of the experiment;
- The second slope was considered flat by the end of the experiment (± 0.05 sec per block);
- The segmented regression found at least one statistically significant breakpoint.

Based on these criteria and a visual inspection of each individual curve, participants were split into two groups (Figure 2.15):

- Plateau group: showed a clear initial improvement followed by stable performance (e.g., participants A, B, C, D). These patients will be included in all subsequent analyses (Chapter 3, Chapter 4, Chapter 6, Chapter 7)
- Non-plateau group: continued to improve throughout the experiment without a clear asymptote (e.g., participants E, F, G, H, I). The absence of a clear plateau suggests that their performance did not stabilize and may have kept improving if the training had lasted longer. These patients will be excluded from all subsequent analyses (Chapter 3, Chapter 4, Chapter 6, Chapter 7).

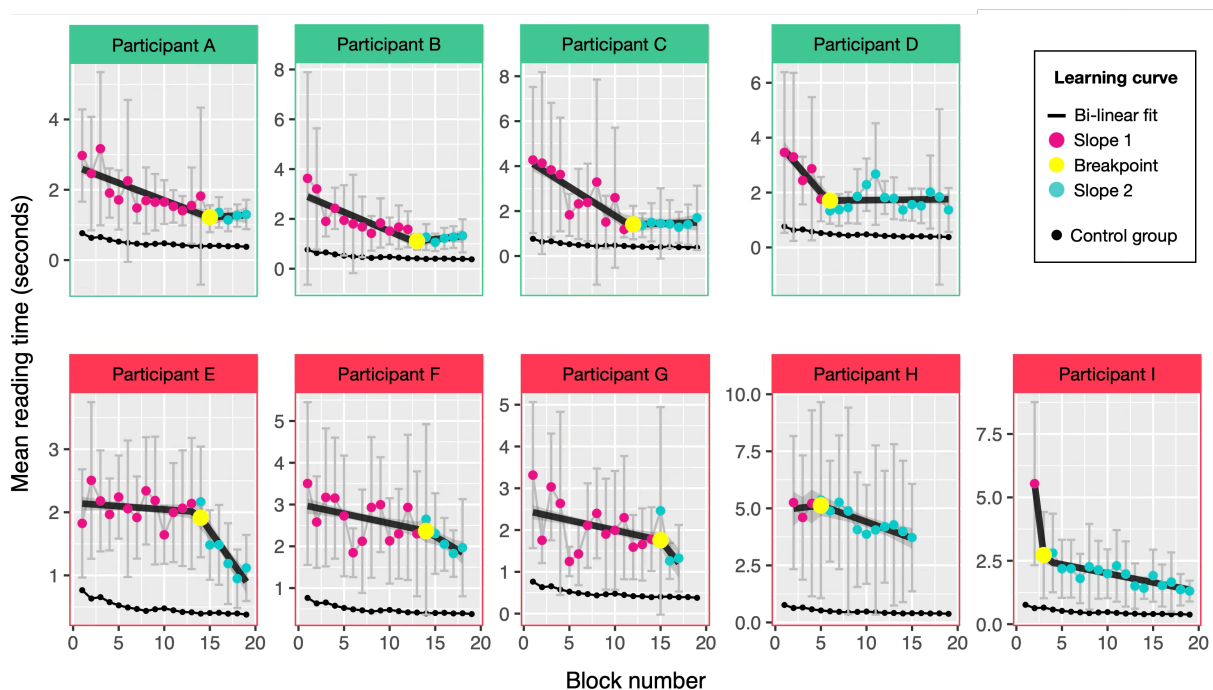


Figure 2.15 shows the resulting individual learning curves. Reading time changes throughout the experiment, for participants in the simulated scotoma group. Subplots show mean word reading time as a function of block number for four representative participants included in the analysis (top row) and five participants excluded from the analysis (bottom row). For all nine participants, the mean reading time values (pink and blue circles) and their standard deviation (gray error bars) are superimposed by a bilinear fit (black solid line), which

breakpoint is marked by a yellow circle. In green, participants A to D (top row) experienced a similar learning pattern: a more or less steep learning curve (in pink) followed by a statistically significant plateau of performance across five blocks or more (in blue). Plateau was defined as a segment which slope was comprised between -0.05 and 0.05 . In red, participants E to I (bottom row), who did not show a significant plateau of performance toward the end of the experiment, were excluded from the final analyses. Average data from the control group (small black circles) are displayed in each subplot for comparison.

6.2 Eye movements data

6.2.1 General fixation processing

Eye-movement data were exported from the eye-tracker as raw EyeLink “.EDF” files, converted to “.asc” files to be processed in R. We imported event logs (fixations, saccades, blinks, messages) and preprocessed them before analysis. Trials were delimited from the onset of the word to the participant’s response message, and only events within these windows were kept. Blinks and saccades were excluded, and initial central fixations at the start of each sentence were removed – as it corresponds to the fixation of a target in the center of the screen, before the sentence display. Very short fixations (< 80 msec) and unusually long ones (> 1000 msec) were discarded, consistent with standard practices in reading research. Fixations were then aligned to the word during which they were displayed, using the timestamps of word onset and offset recorded during the experiment.

6.2.2 In-between fixation processing

For some experimental groups (see Table 2.1), we recorded eye movements while participants read sentences displayed with self-paced reading (SPR). In SPR, sentences are revealed one word at a time via manual button presses controlled by the participant. Occasionally, a single oculomotor fixation spanned the transition between two words (e.g., the end of word n and the start of word $n+1$). If left unprocessed, these fixations, that we labelled as “in-between” fixations, would bias both word-level fixation durations and number, since the entire fixation would be arbitrarily assigned to one word or the other.

Using EyeLink DataViewer, we extracted the onset and offset times of each fixation along with the timestamps marking the beginning and the end of each word. For each in-between fixation (i.e. overlapping two consecutive words), we considered 3 alternative processing strategies.

Option 1: Delete in-between fixations

One approach was to exclude all in-between fixations entirely, due to the process difficulty encountered. However, this meant removing every fixation from any word containing an in-between fixation – not just the overlapping fixation itself. This approach greatly reduced the dataset size; thus, we decided to explore other leads.

Option 2: Assign in-between fixations to majority word

Since we computed the percentage of time spent on each word within a fixation, we considered assigning the entire fixation to the word that was displayed the longest during the in-between. This option works well when the overlap is clearly unbalanced (e.g., 50 ms on word n and 200 ms on word $n + 1$), but becomes problematic when the split is nearly even (e.g., 100 ms vs. 150 ms). In such cases, the choice of assignment is essentially arbitrary, and not representative of what happened during reading.

While options 1 and 2 are simple to implement, both involve an unavoidable loss of precision. Deleting overlapping fixations (option 1) discards potentially meaningful eye tracking data, while assigning the entire fixation to the majority word (option 2) imposes an all-or-nothing decision that can misrepresent the reading process, particularly when the fixation is nearly evenly split. Given that the goal of our analysis was to retain as much information as possible without introducing arbitrary cut-offs, we needed a method that preserved fixation duration and count while accurately reflecting the proportion of attention allocated to each word.

Option 3: Split fixations proportionally

To preserve the total fixation time and avoid arbitrary assignments, we split each in-between fixation into two parts, proportionally to the time spent on each word (Figure 2.16). For example, a 250 ms fixation with 40% on word n and 60% on word $n + 1$ would be split into 100 ms and 150 ms segments, respectively. Fixation counts were also split proportionally (e.g., 0.4 for word n , 0.6 for word $n + 1$ – see Figure 2.16. for the full example). This approach preserved information about both words and normalized the unusually long durations of in-between fixations compared to regular fixations. After splitting, extremely short segments (< 30 ms) or extremely long ones (> 1000 ms) were removed to match standard fixation duration thresholds.

All subsequent analyses reported in this dissertation were conducted using option 3.

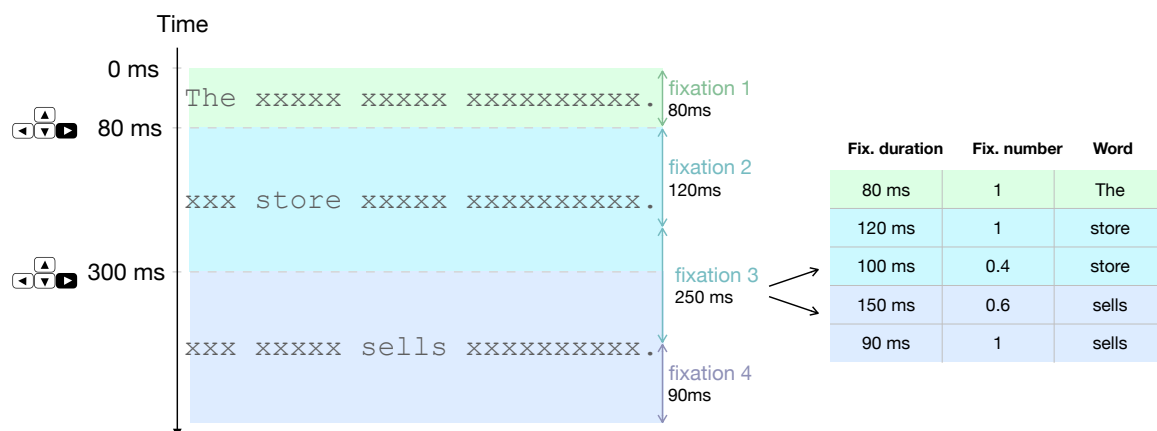


Figure 2.16. Example of in-between fixation processing - fixation 3 begins during the display of word n “store” and ends during the display of word $n + 1$ “sells.” The total fixation duration is 250 ms, with 40% spent during the display of the word “store” and 60% during the display of the word “sells.” During

processing, it is split proportionally into 100 ms for “store” and 150 ms for “sells,” and the fixation count is proportionally distributed (0.4 and 0.6, respectively).

7 Statistical analysis

Statistical analyses were carried out using R and RStudio.

Two types of analyses were systematically performed by fitting linear mixed-effect models using the `lmer()` function:

1. Accuracy analyses – examining predictors’ effects on task accuracy;
2. Reading time analyses – assessing the influence of predictors on reading time;

For experiments involving eye-tracking, we additionally performed:

3. Fixation duration analyses – assessing the influence of predictors on fixation duration;
4. Fixation count analyses – assessing the influence of predictors on the number of fixations.

Each of these four measure was included as a dependent variable in a linear mixed-effects model and transformed using the natural logarithm (\ln) to improve model fit and normalize residuals. In each model, the predictors included both linguistic and visual factors relevant to the study. Random intercepts always included a participant-level effect and were sometimes extended to study-level effects. For each model, the Akaike Information Criterion (AIC) was used to guide selection of the optimal random-effects structure (Zuur et al., 2010). The significance of the fixed effects in each model was then estimated using t-values. Effects were considered significant for t-values greater than 2 or less than -2, corresponding to a 5% significance level in a two-tailed test (Baayen et al., 2008; Gelman & Hill, 2006).

Part II – Disentangling psycholinguistic complexity in eccentric reading

Chapter 3 PREDICTABILITY EFFECTS WHEN READING WITH A SIMULATED CENTRAL SCOTOMA

This chapter investigates how in-context predictability affects reading with eccentric vision, compared to normal vision.

Thirty-five young adults read aloud 304 sentences across two in-lab sessions while eye movements were recorded; twenty-two participants practiced reading with a gaze-contingent simulated central scotoma and the remaining participants served as controls.

When reading with the simulated scotoma, highly predictable words produced a clear performance advantage compared with unpredictable words, especially early in training, and this advantage lessened with practice. Eye-movement analyses showed that the predictability benefit was driven by fewer fixations per word rather than by substantially longer fixations, and the effect was absent under normal central viewing. Together, these results support the idea that readers adapt to limited visual input by relying more on linguistic inference, at least until functional adaptation reduces that dependence.

This work is extracted from: Lapeyre, E., Gala, N., Calabrese, A. (2025). **Beneficial influence of in-context predictability when young adults read with a simulated central scotoma.** *Journal of Vision*, 25(10), doi:10.1167/jov.25.10.6.

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Beneficial influence of in-context predictability when young adults read with a simulated central scotoma

Eole Lapeyre

CRPN CNRS UMR 7077,
Aix-Marseille University, Marseille, France



Núria Gala

LPL CNRS UMR 7309,
Aix Marseille University, Aix-en-Provence, France



Aurélie Calabrèse

CRPN CNRS UMR 7077,
Aix-Marseille University, Marseille, France



1 Introduction

In normal vision, effects of in-context (or contextual) word predictability on reading performance have been documented for many years. In 1995, Bullimore and Bailey showed that skilled readers read meaningful text faster than random strings of words (M. Bullimore & Bailey, 1995). Mr. Chips, an ideal-observer model of reading, exhibited a 30% increase in reading speed when context cues were available, confirming a facilitating effect of word predictability in typical readers (Legge et al., 2002). Syntactic and semantic relationships between words make continuous text more predictable than random words. From an eye-movement perspective, when a word can be predicted from context, readers often skip it or spend relatively little time fixating on it (Ehrlich & Rayner, 1981). Computational models of eye-movements control, such as E-Z Reader (Reichle et al., 1998, 2003) and SWIFT (Engbert et al., 2005) integrate predictability as one of the two main linguistic variables that influence eye-movement decisions – when and where to move the eyes –, the other one being word frequency.

In the case of CVL, which requires reading with eccentric vision, in-context word predictability has also been studied, yielding discrepant results and several potential hypotheses. One of them suggests that decoding visually degraded input is costly for individuals with CVL, who may then have fewer cognitive resources available for contextual analysis compared to normal readers. This hypothesis is supported by results from Sass and collaborators in 2006, showing that removal of sentence context through word scrambling had a greater negative impact on normal compared to low vision (Sass et al., 2006). However, these results were obtained from a heterogeneous group of low vision individuals, including both CVL and other visual deficits. A second hypothesis suggests that in-context gain is equivalent for CVL and control readers. This is supported by empirical data showing a strong increase in reading speed with context, but no significant difference between normal vision and CVL reading (Fine & Peli, 1996) or between central and peripheral reading with normal vision (Fine, Hazel, et al., 1999). Other authors have also shown a 15 to 30% reading-speed advantage for sentences over random words in a heterogeneous group of readers with low vision, which is roughly consistent with findings from controls (Legge et al., 1989, 2002). A

third hypothesis suggests that if individuals with CVL can decode text well enough, they may rely more on linguistic inferences. In doing so, they would rely more on predictability compared to normal readers and experience a stronger context advantage. This hypothesis is supported (M. Bullimore & Bailey, 1995), who reported higher reading speed for meaningful text compared to random words for both control and AMD readers, the advantage being significantly larger for AMD. To date, the influence of in-context predictability on reading performance in the presence of a central scotoma is not clearly identified. Importantly, it is impossible to objectively quantify the amount of adaptation to central field loss in patients tested at one time point during their pathology. Therefore, none of the studies described above involving pathological CVL took into account the inter-individual differences in adapting to the use of eccentric vision, possibly explaining results discrepancies. Given the recent investigations of psycholinguistic word features when reading with CVL and their obvious relationship with predictability, it seems timely to re-evaluate the in-context word predictability effects when reading with eccentric vision.

The work presented in this chapter aims to investigate the effect of in-context word predictability when reading with eccentric vision, using a simulated central scotoma, while taking into account lexical word features. A multifactorial approach was chosen, accounting for the fact that reading limitations with eccentric vision are likely to result from multiple contributing factors. Based on evidence from eye-movement research and computational models, such as E-Z Reader and SWIFT, we predict that high-predictability words will receive shorter fixation durations and be skipped more often than low-predictability words, and that this predictability benefit will be larger with eccentric vision than with central vision. Because degraded visual input from reading in eccentricity reduces the reliability of bottom-up information, we further expect readers to rely more on top-down linguistic inference; as participants adapt to the simulated scotoma and become more efficient eccentric readers, the need for such inference - and thus the magnitude of the predictability advantage - should decline with practice.

To investigate this hypothesis, we examine the influence of predictability on reading accuracy and reading time. Given that changes in reading time can be attributed to either a change in fixation number, a change in fixation duration or both, we also analyzed these two measures to identify underlying factors of performance changes. Each of these analyses takes into account the lexical and visual word features that have been shown to have a significant influence on reading speed in individuals with acquired CVL (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019).

Importantly, we wanted to test whether predictability effects were influenced by the individuals' fluency and their adaptation to the presence of the scotoma. Indeed, for our hypothesis to be validated, we must show that the amplitude of the in-context predictability effect reduces as readers adjust to the presence of the scotoma and need to rely less on inference. Therefore, we tested normally sighted participants to whom we simulated a gaze-contingent central scotoma over several practice sessions, to record performance over the adaptation process since the first exposure to the simulated scotoma.

2 Methods

The general methodology for this experiment is described in Chapter 2. All participants were healthy young adults who read sentences using the self-paced reading (SPR) paradigm. One group read with a simulated gaze-contingent central scotoma while the other group served as a control group (Table 3.1).

The corpus of sentences was corpus #1, from (Albregues et al., 2019), consisting in 304 pairs of sentences. Each participant read one sentence from each pair, reading 304 sentences in total across two in-lab sessions. At the time of the experiment, we used the predictability measure created by (Albregues et al., 2019)'s cloze task, implying that we only processed the target words.

Each participant read only one sentence per pair, with an equal number of predictable and unpredictable sentences. Sentences were organized into 19 blocks of 16 sentences each (Figure 3.1). Within a block, sentences were presented in a random order.

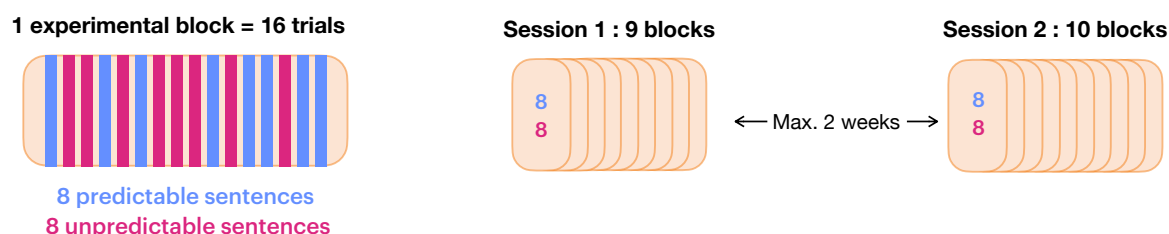


Figure 3.1. Sentences were presented within experimental blocks of 16 trials where 8 predictable and 8 unpredictable sentences were randomly displayed. Each participant read 9 blocks during the first testing session and 10 blocks during the second session.

Both groups performed the experiment while their eye movements were recorded by an eye tracker. For each target word, we recorded reading time, average fixation duration and fixation count.

	Self-Paced reading	Sentence corpus	Experimental setup	Outcome measures
Healthy young adults				
Control	N = 13 (6F / 7M) Mean age = 24.3 ± 1.8	Corpus #1 304 sentences	Computer screen + eye tracker	Reading time Fixation number Fixation duration
Simulated scotoma	N = 22 (15F / 7M) Mean age = 22.7 ± 2.4			

Table 3.1. Summary of experimental groups and conditions included in this study, as well as the corpus, experimental setup and outcome measures. In the scotoma group, 5 participants who did not reach a learning plateau (see Chapter 2 Section 6.1.2 for details) were not included in this study.

3 Results

3.1 Participants

Table 3.2 shows demographic information and reading performance measures for the 35 participants included in the analyses.

	Demographics			Reading performance (MNREAD)	
	Gender		Age (years) (Mean ± std)	MRS (words/minute) (Mean ± std)	CPS (logMAR) (Mean ± std)
	Female	Male			
Control group	6	7	24.3 ± 1.8	176 ± 26	0.05 ± 0.14
Scotoma group	15	7	22.7 ± 2.4	186 ± 16	0.07 ± 0.16

Table 3.2. Characteristics of the 35 participants included in the analysis.

3.2 Accuracy (Analysis 1)

Accuracy was excellent across all trials, participants, and conditions (scotoma versus control): 99.9% accuracy in the control group (SD=0.7) and 99.6% accuracy in the artificial scotoma group (SD=1.6). Model 1 revealed no significant effect of predictability on accuracy and no significant difference in accuracy between the two conditions (scotoma versus control).

3.3 Reading time (Analysis 2)

Results from Model 2 are summarized in Table 3.3 and plotted in Figure 3.2. For the control group and during the first block of the experiment, participants' average reading time was 0.60 seconds for unpredictable words and 0.59 seconds for highly predictable words (Figure 3.2– dashed orange line). This difference was not significant ($t=-0.34$). As the number of blocks increased, reading time for unpredictable words decreased significantly from 0.60 seconds to 0.34 seconds from first to last block, showing a significant effect of practice in the control group ($t=-16.85$). Still for the control group, there was no significant interaction between predictability and block number ($t=-0.30$), indicating that the same effect of practice was observed for predictable words, with a significant decrease from 0.59 to 0.33 seconds from first to last block. Hence, predictability effect for that group remained null throughout the experiment, and reading time was improved only through practice, regardless of the level of predictability.

In the presence of the simulated scotoma, reading time of unpredictable words increased significantly by a factor of 4.18 compared to the control group (2.51 against 0.60 seconds) during the first block. We also found a significant effect of predictability in the scotoma group

($t=-10.72$): during the first block, reading time decreased from 2.51 seconds to 1.62 seconds between low and high predictability (Figure 3.2 – solid orange line). Similarly to the control group, we found a significant effect of practice when learning to read with the simulated scotoma ($t=-2.72$): when predictability was at its lowest, reading time decreased from 2.51 seconds in the first block to 1.29 seconds in the last block. On top of that practice effect, we found a significant interaction between predictability, block number and condition, meaning that the effect of predictability changed over the course of the experiment, but only in the presence of a scotoma: as block number (and therefore practice) increased, the amplitude of the predictability effect decreased significantly ($t=3.10$ – Figure 3.2). Overall, word length and word frequency had a significant effect on reading time in the control group (respectively $t=2.71$ and $t=-2.47$), which was not significantly different in the scotoma group (respectively $t=-1.77$ and $t=-1.52$).

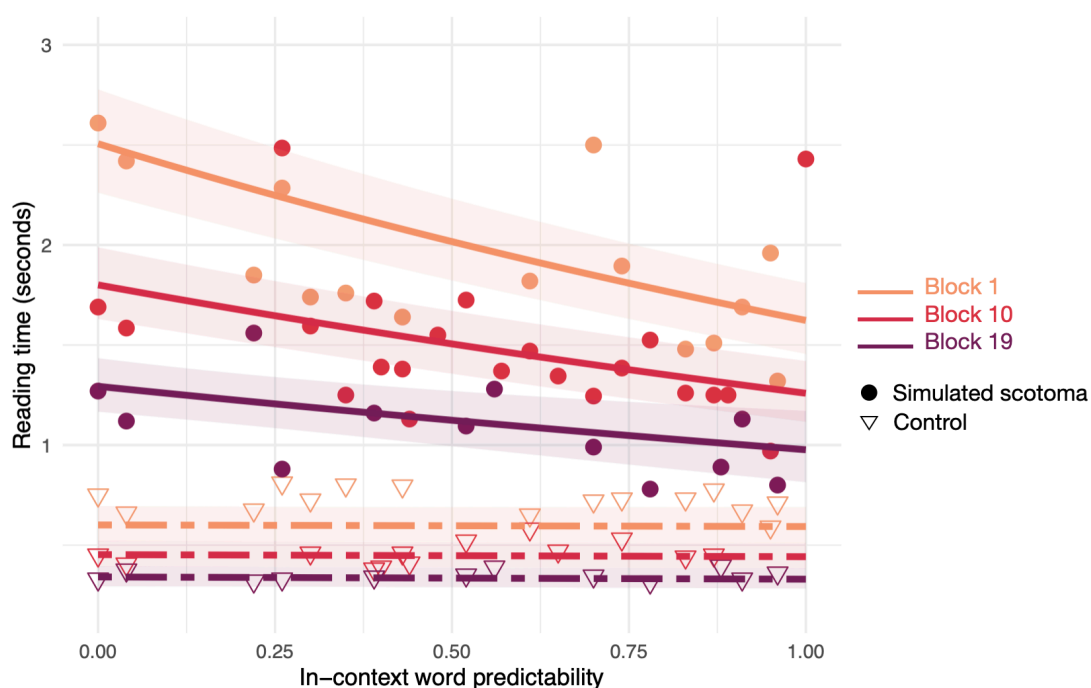


Figure 3.2 Reading time as a function of in-context word predictability, grouped by condition and block number. Data points show median word reading time for each value of predictability, broken down by condition (scotoma in filled circles vs. control in open triangles) and block number (orange for the first block, red for the middle block and purple for the last block). Lines represent slopes estimated by Model 2, along with their 95% confidence intervals (solid lines for the scotoma group; dashed lines for the control group).

3.4 Oculo-motor pattern changes

As shown in Analysis 2, adaptation to the presence of the scotoma significantly decreases reading time over the course of the experiment. This performance improvement is likely to reflect changes in oculo-motor behavior, since a decrease in reading time can be attributed to either a decrease in fixation number, a decrease in fixation duration or a mixture of both. Visual inspection of the eye traces (Figure 3.3) suggests that reading with a simulated scotoma initially leads to an increased number of fixations and more erratic eye movement patterns. By the final block of the experiment, fixation patterns tend to resemble those of a

control participant. We analyzed fixation number (Analysis 3) and fixation duration (Analysis 4) to identify the underlying factors of these performance changes.

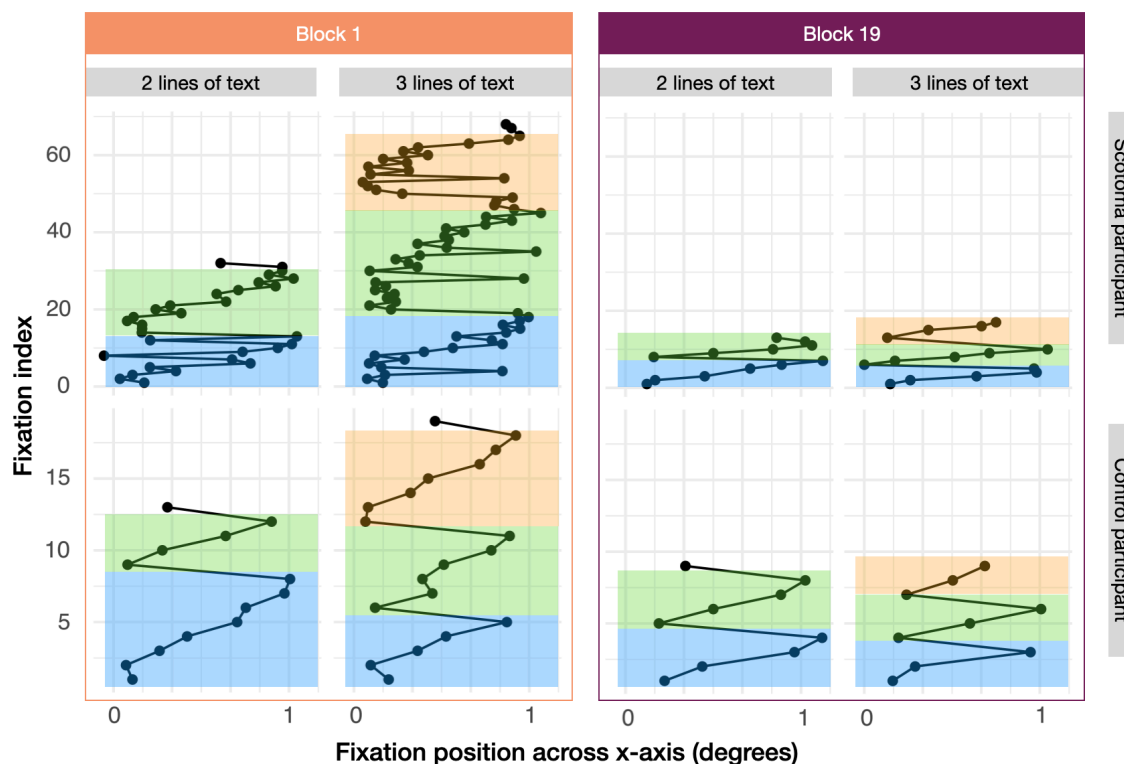


Figure 3.3 Eye movement traces from two representative participants: one reading with a simulated scotoma (top row) and a control participant (bottom row). Each panel represents a sentence, displayed across 2 or 3 lines, color-coded by line: blue (1st), green (2nd) and orange (3rd). Left panels correspond to the first experimental block and right panels to the final block. Each dot corresponds to a fixation, with horizontal positions normalized between 0 (left) and 1 (right) for each sentence. The y-axis (fixation index) indicates the chronological order of fixations.

3.4.1 Fixation number (Analysis 3)

Results from Model 3 are summarized in Table 3.3 and plotted in Figure 3.4. For the control group and during the initial block of the experiment, participants' average number of fixations per target word was 1.55 for unpredictable words and 1.46 for predictable words (Figure 3.4 – dashed orange line). This difference was not significant ($t=-1.19$), which indicates that at the beginning of the experiment, the number of fixations were similar for control participants, regardless of the level of predictability. The number of fixations required to read low-predictability words decreased significantly from 1.55 fixations per word to 1.08 from first to last block. There was no significant interaction between block number and predictability for the control group ($t=0.65$), which means that the predictability effect for the control group remained null throughout the experiment, and that fixation number was only improved through practice, regardless of the level of predictability.

Overall, there was a significant effect of the presence of the artificial scotoma on the number of fixations ($t=13.49$). At the lowest predictability and during the first block of the experiment,

the average number of fixations increased from 1.55 in the control condition to 7.24 in the scotoma condition. Contrary to the control group, there was a significant effect of predictability on the average number of fixations in the scotoma group ($t=-8.08$). Hence, across the first block, while low-predictability words required 7.24 fixations, high-predictability words only yielded an average of 4.29 fixations. As for the control group, there was a significant effect of block number when reading with a scotoma ($t=-5.58$). When predictability was low, the number of fixations decreased from 7.24 in the first block to 3.71 in the last block. Moreover, there was a significant interaction between predictability and block number in the scotoma condition: the higher the block number, the smaller the amplitude of the predictability effect ($t=3.47$).

Finally, among the word characteristics, only the word target length showed a significant effect on fixation number in both groups: the longer the word the higher the number of fixations. Each word length increase of 1 character leads to a significant increase in reading time by a factor of 1.05 in the control group and of 1.02 in the scotoma group.

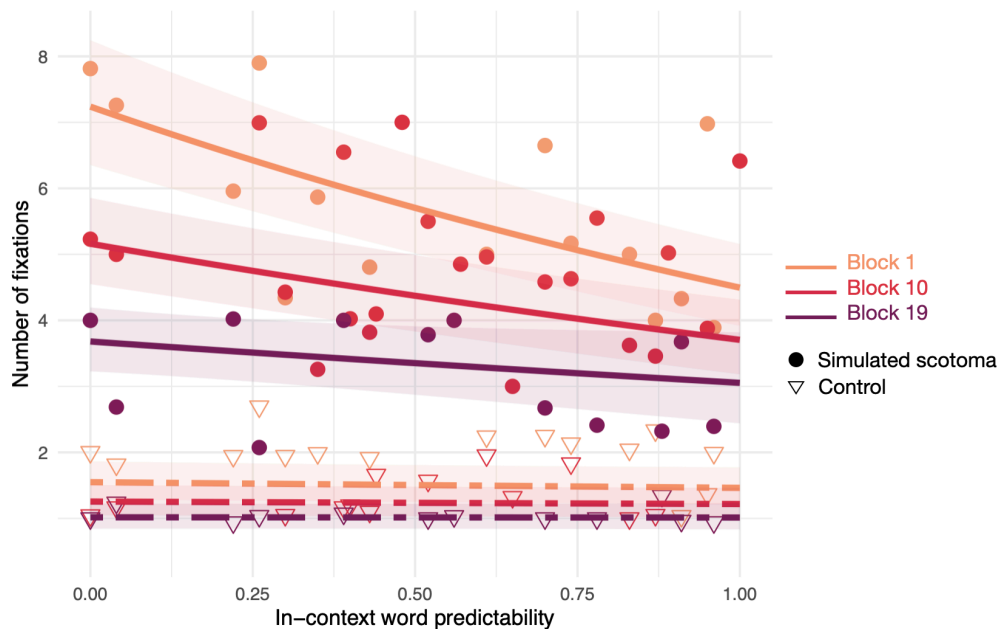


Figure 3.4 Fixation number as a function of in-context word predictability, grouped by condition and block number. Data points show the median fixation number of target words, for each value of predictability, broken down by condition (scotoma in filled circles vs. control in open triangles) and block number (orange for the first block, red for the middle block and purple for the last block). Lines represent slopes estimated by Model 3, along with their 95% confidence intervals (solid lines for the scotoma group; dashed lines for the control group).

3.4.2 Fixation duration (Analysis 4)

Results from Model 4 are summarized in Table 3.3 and plotted in Figure 3.5. We found no significant effect of the presence of the simulated scotoma on the average fixation duration (Table 2; $t=0.65$). During the first block of the experiment, no significant effect of predictability was observed on fixation duration for either the control ($t=-0.41$) or the scotoma group ($t=0.86$). For both groups, the average fixation duration did not significantly decrease from block to block (Figure 3.5).

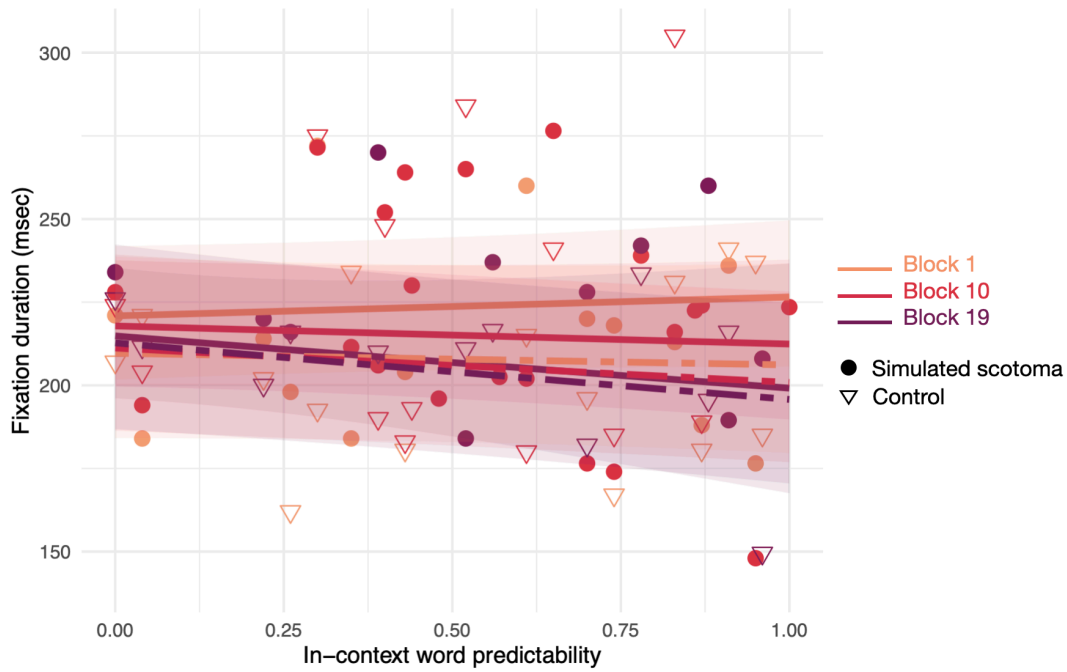


Figure 3.5 Fixation duration as a function of in-context word predictability, grouped by condition and block number. Data points show the median fixation duration (in ms) of target words, for each value of predictability, broken down by condition (scotoma in filled circles vs. control in open triangles) and block number (orange for the first block, red for the middle block and purple for the last block). Lines represent slopes estimated by Model 4, along with their 95% confidence intervals (solid lines for the scotoma group; dashed lines for the control group).

	Model 2		Model 3		Model 4	
	Reading time		Fixation number		Fixation duration	
	Est.	(t-value)	Est.	(t-value)	Est.	(t-value)
(Intercept)	-0.51 ^{***}	(-6.9)	0.44 ^{***}	(4.6)	5.35 ^{***}	(80.8)
Predictability	-0.01	(-0.3)	-0.06	(-1.2)	-0.02	(-0.4)
Block number	-0.03 ^{***}	(-16.9)	-0.02 ^{***}	(-10.0)	8e ⁻⁴	(0.4)
Word length	0.01 ^{**}	(2.7)	0.05 ^{***}	(7.7)	-0.02 ^{***}	(-3.3)
Word frequency	-2e ^{-4*}	(-2.5)	-1e ⁻⁴	(-1.6)	-4e ⁻⁵	(-0.5)
Word number of neighbors	-3e ⁻³	(-1.4)	-3e ⁻³	(-1.5)	6e ⁻⁴	(0.3)
Scotoma	1.43 ^{***}	(16.0)	1.54 ^{***}	(13.5)	0.05	(0.7)
Scotoma:Predictability	-0.42 ^{***}	(-10.7)	-0.42 ^{***}	(-8.1)	0.04	(0.9)
Scotoma:Block number	-5e ^{-3**}	(-2.7)	-0.01 ^{***}	(-5.6)	-2e ⁻³	(-1.0)
Scotoma:Word length	-8e ⁻³	(-1.8)	-0.03 ^{***}	(-4.1)	0.02 [*]	(2.5)
Scotoma:Word frequency	-1e ⁻⁴	(-1.5)	-1e ⁻⁴	(-1.4)	-6e ⁻⁵	(-0.7)
Scotoma:Word neighbors	5e ^{-3*}	(2.5)	5e ⁻³	(1.9)	5e ⁻⁴	(0.2)
Control:Predictability:Block	-1e ⁻³	(-0.3)	3e ⁻³	(0.7)	-4e ⁻³	(-0.9)
Scotoma:Predictability:Block	0.01 ^{**}	(3.1)	0.01 ^{***}	(3.5)	-2e ⁻³	(-0.7)

Table 3.3. Fixed effect estimates from Models 2, 3 and 4. All models share the same fixed and random structure, except for the dependent variable, which are respectively word reading time (Model 2), fixation number (Model 3) and fixation duration (Model 4). Models' estimates are reported in the table, along with their t-values. * p<0.05 ** p<0.01 *** p<0.001

4 Discussion

The goal of the present work is to investigate the hypothesis that, compared to central vision, eccentric vision yields a stronger in-context predictability advantage because readers rely more on linguistic inferences to compensate for the degraded visual input, at least until they adapt their behavior to the presence of the simulated scotoma. To do so, we forced young normally sighted participants to read with eccentric vision by imposing a gaze-contingent simulated scotoma. We estimated how in-context word predictability affects reading time and accuracy, both with and without a simulated scotoma, and how this effect changes over time and practice while taking into account visual and lexical features of the words. Underlying changes in eye movement patterns were also investigated.

Our first main result is that in-context predictability shows a strong significant effect on reading time in the presence of a simulated scotoma. Highly predictable words are read more than 1.5 times faster compared to non-predictable ones, representing a 35 % increase in reading speed, solely explained by the access and use of contextual information. This first result goes against the hypothesis according which, decoding eccentric (and therefore degraded) visual input requires so much cognitive resources, that readers do not have enough available left to process and take full advantage of contextual cues (Sass et al., 2006). In contrast, we found no significant effect of in-context predictability for control readers, for whom average reading time remained constant, regardless of the predictability of a word within a given sentence. These results are in favor of the hypothesis suggesting that individuals reading with eccentric vision can use linguistic inference efficiently, experiencing a stronger context advantage compared to normal readers. By extension, one may argue that this reasoning could also apply to individuals with CVL, forced to use eccentric vision to read. This rationale would be in line with the results reported in actual patients by Bullimore & Bailey (1995), who found that contextual cues increase reading speed more dramatically in AMD than in normally sighted readers (M. A. Bullimore & Bailey, 1995). However, our results differ on several major points, likely due to methodological differences.

First, we found a smaller in-context advantage in the presence of a simulated scotoma, with a 1.5 decrease factor of reading time, where Bullimore & Bailey reported a 2.9 increase factor of reading speed for in-context words (M. A. Bullimore & Bailey, 1995). The nature of the reading material and our distinct ways to estimate the influence of context, may explain this difference. In the present study, target words were presented within a grammatically correct sentence and given a precise measure of predictability, ranging from 0 to 1, previously measured with a cumulative cloze task in a large cohort of control readers (Albregues et al., 2019). Therefore, each word was attributed an empirical measure of predictability, estimated from the semantical and syntactical context of the sentence it was presented in. On the other hand, Bullimore and Bailey compared meaningful texts against series of random words, estimating the overall influence of contextual cues on reading speed, with no specific control over the level of word predictability within texts. Therefore, the present study allows to estimate the influence of in-context predictability on a more precise scale. Additionally,

these authors emphasized that average word length varied across their experimental conditions, possibly explaining part of the effect they reported, whereas word characteristics such as length, frequency and even orthographic neighborhood size were controlled for in the present study. Finally, while Bullimore and Bailey reported results from individuals with pathological CVL, the present work focuses on eccentric reading from scotoma simulation. As already mentioned, differences in the use of peripheral vision between patients with CVL and healthy individuals are subject to debate (S. T. L. Chung & Legge, 2025) and are very likely to explain part of the discrepancy in the predictability advantage amplitude reported between pathological and simulated conditions of eccentric reading. This will be addressed in Chapter 7.

The second major difference between our results and the ones from Bullimore & Bailey relates to the in-context predictability effect reported for the normal vision group. In the present work, control readers do not benefit from highly predictable words. Yet, several studies have demonstrated that predictability facilitates reading in typical readers (M. Bullimore & Bailey, 1995; Legge et al., 2002). Such discrepancy may be due to the use of different reading paradigms. Indeed, the sequential reading imposed by the Self-Paced Reading paradigm in the present work, may not allow to capture the sensitive predictability effect (in the range of milliseconds) experienced by control readers. Indeed, as discussed in Chapter 2 Section 4.3, the SPR paradigm tends to significantly slow down the reading process, compared to natural reading. We must also consider that different context effects may exist for different text displays. Indeed, for dynamic forms of text presentation, such as Rapid Serial Visual Presentation (RSVP) reading and drifting text, stronger context effects have been reported in normal readers (Fine & Peli, 1996).

Our second main result is that the effect of in-context predictability is modulated by the amount of practice with eccentric reading. In the scotoma group, the amplitude of the predictability effect decreased significantly as exposure time to the scotoma increased. At first exposure to the simulated scotoma, average reading time ranged from 2.51 seconds for low predictability words to 1.62 second for highly predictable words, representing a 35% improvement in reading speed, solely accounted for by predictability influence. At the end of the experiment, this improvement got reduced to 22%, with reading time ranging from 1.29 to 1.0 second. This progressive decrease in amplitude implies that readers rely less and less on linguistic inference, which probably results from their adaptation to eccentric reading and the potential development of compensatory strategies. One could argue that this modulation of the predictability effect through practice might explain the discrepant literature results on in-context gain reported in low-vision individuals (Legge et al., 1989; Fine & Peli, 1996; Fine et al., 1999), for whom it was impossible to control for the amount of practice with eccentric vision.

In the literature, overall context effects are reported to be smaller in good than in poor readers (Briggs et al., 1984). Such distinction between good and poor readers is mainly used for children learning to read and relates to their developing cognitive and linguistic skills. Still, it

pertains to the achievement of proficient reading ability, which is impaired when forced to read with eccentric vision. If we consider our participants forced to read with a simulated scotoma as being “poor readers” at the beginning of the experiment and “good (or at least better) readers” towards the end, our results align with the literature. Even more interesting, one could argue that if participants had been given more exposure time to the scotoma, the amplitude of the effect would have kept decreasing, potentially getting closer to the null effect observed in the control group. This point, which remains to be tested, is in favor of enforcing visual rehabilitation and daily practice of reading for patients with acquired CVL, in order to reduce the negative influence of low-predictability contexts.

Characterizing specific eye movement changes in response to eccentric reading adaptation was not the focus of the present work. However, identifying underlying components of performance changes as a function of predictability and adaptation required to describe fixation characteristics. It appears that changes in reading time yield by variations of in-context word predictability could be attributed to changes in the total number of fixations, whereas fixation duration remained constant. Indeed, analyses of reading time (Table 3.3; Figure 3.2) and fixation number (Table 3.3; Figure 3.4) revealed a similar effect of in-context predictability (both in terms of amplitude and significance level), while no effect was found on fixation duration (Table 3.3; Figure 3.5). When reading with eccentric vision, highly predictable words required significantly less fixations than non-predictable words (from 35 % less at the beginning of the experiment, to 22 % less at the end). This result is in line with findings from numerous studies on young healthy readers, which show that words that are shorter, higher in lexical frequency, or more predictable yield shorter reading times and have lower fixation probabilities (Ehrlich & Rayner, 1981; Kliegl et al., 2004; Rayner et al., 2006; Choi et al., 2017). Hence, most studies on reading use word skipping as a proxy to estimate the influence of in-context predictability, starting from the postulate that, if the reader can make efficient use of predictability, highly predictable words are more likely to be skipped. Because the self-paced reading imposes to fixate on each word, skipping rates could not be investigated in the present study, preventing us from comparing our results to current literature results on predictability using word-skipping.

Since reading in eccentric vision is very costly, participants could have adopted a risky reading strategy, similar to that observed in healthy older adults (Choi et al., 2017; Paterson et al., 2020) - relying more on contextual cues, skipping or partially processing some words, thus making fewer individual word fixations. However, this was not observed in our group of eccentric vision readers. Instead, they consistently prioritized accuracy over speed, carefully reading each word before moving to the next one. The adaptive strategies selected by young, healthy participants for peripheral reading contrast with those typically seen in healthy older adults, who often adopt a risky reading approach to compensate for slower processing. Because of its word-sequential reading nature, the self-paced reading paradigm may have also muted any tendency toward a risky strategy by requiring participants to process each word individually without previewing surrounding words, reinforcing a word-by-word reading approach.

It is worth mentioning that, aside from the question of predictability, reading with a simulated scotoma showed a strong significant impact on the number of fixations but did not alter significantly the overall fixation durations. These results are consistent with the ones reported by (Scherlen et al., 2008), who observed that the number of saccades almost doubled when reading short sentences under simulated central scotomas, while fixation duration was not significantly increased (216 ms to 241 ms). Yet, our results differ in amplitude, from the report of a recent investigation of altered eye movements during reading with simulated scotomas (H. Yu & Kwon, 2023). In this work, the authors showed that when normally sighted individuals had to read a text “naturally”, compared to reading with a 10° diameter simulated central scotoma and no prior training, their number of fixations increased significantly by 89% and their fixation duration increased significantly by 13 % (from 217 to 245 ms). In the present study, we report a slightly smaller change in fixation duration, representing a non-significant 10% increase (from 206 ms for the controls to 226 ms with the scotoma, during the first block and for high predictability words). The average fixation number, however, was more dramatically increased in the present work, with a 195% increase when reading with a simulated scotoma. This large difference translated into reading performance, with a reading speed increase factor of 2 between the two conditions in (H. Yu & Kwon, 2023), against a reading time decrease factor of 3 in our study. These differences could be attributed to the different reading tasks used, involving different processes: sentence versus text reading on one hand, mixed with natural versus self-paced reading on the other one.

Finally, the present work adds to the numerous studies using gaze-contingent scotoma simulation to investigate eccentric reading. While PRL establishment can take up to six months from the onset of a pathological bilateral central scotoma (Crossland et al., 2005), PRL-like behavior has been reported to develop rapidly (within the range of hours) in normally sighted subjects viewing with an artificial central scotoma (Kwon et al., 2013; Liu & Kwon, 2016; Walsh & Liu, 2014). Here, participants in the scotoma group read between 2.5 and 4.4 hours with a simulated scotoma (mean \pm SD = 3.3 \pm 0.5). 81% of them showed learning curves with stable performance for the last 5 blocks or more (Section 6.1.2 from Chapter 2), suggesting that this amount of time was sufficient for them to adapt and learn an efficient strategy to deal with the occlusion of their central field, without any evidence that this constitutes a PRL-like behavior. Yet, examining how participants adjust their eye movement patterns to the presence of a simulated scotoma to achieve functional reading should be investigated further to understand how it relates to the longer time course of PRL(s) development in people with naturally occurring central scotomas (Legge & Chung, 2016; Ağaoğlu et al., 2022).

5 Conclusion

In conclusion, the results presented here seem to confirm that eccentric reading, which limits optimal visual access to text, yields a stronger in-context predictability advantage compared to central vision, because readers rely more on linguistic inferences to compensate for their weaker visual input. This effect appears to be driven solely by the total number of fixations required to identify words. Moreover, this effect mainly impacts eccentric readers in the early stages of their practice.

When interpreting the present results, one must remain aware that the normal periphery in young adults is not a perfect model for reading in the presence of central vision loss (S. T. L. Chung & Legge, 2025) and should be very cautious when making predictions about actual patients with CVL. Still, in the hypothesis that these results could apply to pathological CVL, individuals who have stopped reading or have not developed effective peripheral viewing strategies may be most influenced by context effects. Thus, the need to enforce patients' visual rehabilitation and daily practice of reading in the early stages of their binocular impairment to promote adaptation and reduce the negative influence of low-predictability contexts (on top of the solely positive effect of practice with eccentric reading). Lastly, one must consider that the present results may not apply throughout the life span. Indeed, in normal vision, the influence of age on the effect of word predictability has been investigated, with conflicting results. Some studies report no influence of age, while others suggest a greater facilitation of predictability for younger readers (Kliegl et al., 2004a) or, conversely, a greater facilitation effect for older readers (Steen-Baker et al., 2017). To address these limitations, the influence of in-context predictability will be re-evaluated in both pathological and older healthy readers in Chapter 6.

Chapter 4 COMPARING ORTHOGRAPHIC SIMILARITY MEASURES WHEN READING WITH A SIMULATED CENTRAL SCOTOMA

This chapter investigates whether and how orthographic similarity between a word and its neighbors affects reading when central vision is intact versus with a simulated central scotoma.

Forty native French readers performed a monocular self-paced sentence reading task while eye movements were recorded with an eye-tracker. Two common similarity metrics (N and OLD20) were compared, and reading performances were tracked across 19 practice blocks of 16 sentences. Reading time and fixation measures (duration and count) were analyzed for each word using mixed-effect models.

Both groups were sensitive to orthographic similarity, but the pattern differed: with a simulated scotoma, high similarity produced a clear reading penalty early in training, while under normal viewing the similarity effect was smaller and showed an opposite baseline tendency. In both cases, the influence of similarity attenuated with practice (to the paradigm for the control group, and to the paradigm and the scotoma for the scotoma group).

When both metrics were included in the same model, OLD20 accounted for variance that was most predictive of slowed reading in the scotoma condition, whereas Coltheart's N did not explain additional variance once OLD20 was included. Eye-movement analyses revealed that the cost of high similarity between a word and its neighbors was driven primarily by an increase in the number of fixations per word rather than by changes in fixation duration. These findings identify OLD20 as the preferred metric for studying orthographic similarity when central vision is compromised and suggest that practice improves efficiency by reducing fixation count.

This work is extracted from a ready-to-submit manuscript and was presented at the **2024 French Research Group meeting (GDR Vision)**, and at **ARVO 2024**.

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1 Assessing the influence of Orthographic 2 Similarity when Reading with Eccentric 3 Vision: Coltheart's N against OLD20

4 Eole Lapeyre¹, Aurélie Calabrèse¹

5

6 ¹ CNRS UMR 7077, Aix-Marseille Univ., Marseille, France.

7

1 Introduction

Orthographic similarity - the degree to which a word resembles other words in the lexicon - plays a critical role in visual word recognition (Andrews, 1997; Grainger & Jacobs, 1996). In normally sighted readers, a larger orthographic neighborhood facilitates lexical access, producing shorter fixation durations and faster reading times (Perea & Rosa Martínez, 2000; Sears et al., 1995). In contrast, a recent study with CVL patients revealed the opposite pattern when reading with eccentric vision: the classical measure of orthographic neighborhood size (Coltheart's N) becomes inhibitory, slowing reading as the number of close neighbors increases (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). This inhibitory effect is modulated by individuals' reading habits: it is especially pronounced in patients who do not read frequently and is attenuated when words are highly predictable from context. These findings suggest that degraded foveal input increases visual ambiguity, making it harder to discriminate among competing lexical candidates. The studies cited above all investigated the impact of orthographic neighborhood using Coltheart's N (Coltheart et al., 1977), which has been the standard metric for several decades.

Yet, Perea's review highlights several limitations of Coltheart's N: it treats all neighbors as equally influential, ignores more distant neighbors that may still affect recognition, and provides only a discrete neighborhood count (Perea, 2015). The Orthographic Levenshtein Distance (OLD20), which is now becoming one of the most employed neighborhood measure in visual word recognition research (Grainger et al., 2012; Perea, 2015), overcomes these limitations by offering a more sensitive alternative (Yarkoni et al., 2008). OLD20 computes the average number of letter insertions, deletions, or substitutions required to transform a word into its 20 closest neighbors.

Figure 4.1 illustrates how the OLD20 metric captures visually confusable neighbors beyond those included in Coltheart's N. For example, while *gown* and *town* differ from *down* by one letter substitution (included in N), *clown* requires an insertion and a substitution. Such words, excluded from N but included in OLD20, may be especially confusable when visual input is degraded.

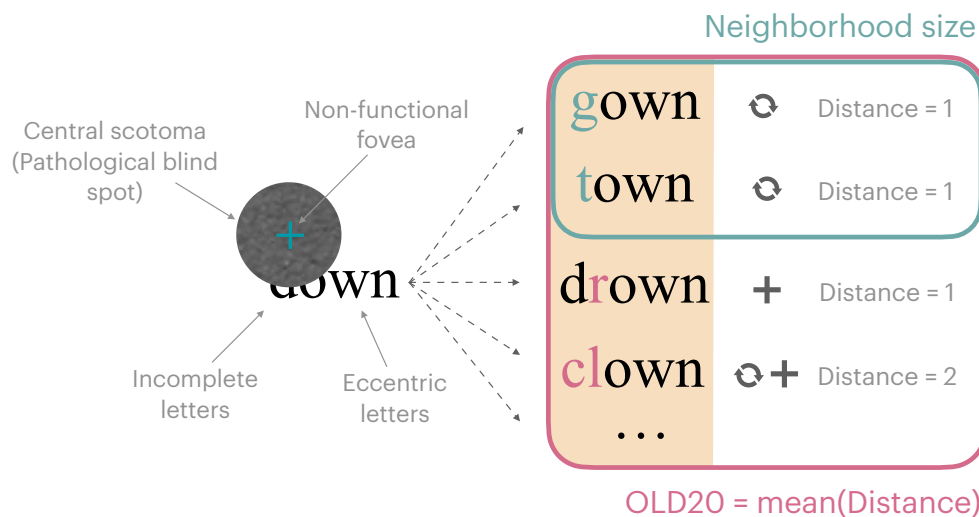


Figure 4.1 Four of the twenty words that are used to compute the old20 measure of the word *down*. *Gown* and *town* are strict neighbors (circled in green), as they require one substitution to be created from the target word. They would be included in Coltheart’s N. *Drown* also requires one computation, but it’s an addition, and *clown* requires 2 additions. They would not be included in Coltheart’s N, but in the OLD20 measure (circled in pink). Because of the scotoma often hiding parts of the text, the word *down* could be easily confused with some neighbors. The most confusable neighbors are not always the ones included in Coltheart’s N, that is why we decided to broaden this measure, by investigating OLD20.

According to the dual-route model of orthographic processing by (Grainger & Ziegler, 2011), visual word recognition engages both a coarse-grained route, enabling rapid but relatively imprecise identification of approximate letter order and global word shape, and a fine-grained route, which encodes precise letter identity and position for accurate but slower lexical access. Building on this framework, we propose that when visual input is degraded, as in eccentric reading, the reliability of coarse, shape-based cues may be reduced, forcing greater reliance on the fine-grained route. Because this route is slower and more effortful, we further hypothesize that words with many visually similar neighbors would be especially difficult to read: when coarse cues cannot quickly rule out competitors, careful letter-by-letter discrimination should be required, and high orthographic similarity may increase the likelihood of confusion and yield longer reading time.

The present study tests this prediction by comparing the effects of OLD20 and Coltheart’s N on reading with and without a gaze-contingent simulated central scotoma. We hypothesize that words with low OLD20 values (i.e., high similarity with closest neighbors) will elicit longer reading times and longer fixations under visual degradation, reflecting increased competition among similar word forms. And because OLD20 captures a broader range of potential competitors than N, we also expect OLD20 to account for more variance in reading performance than N, especially in the central scotoma reading condition. In the long run, identifying a significant difference in the influence of OLD20 vs N during reading could assist the development of reading aids specifically tailored to the CVL population.

2 Methods

The general methodology for this experiment is described in Chapter 2. All participants were healthy young adults who read sentences using the self-paced reading (SPR) paradigm. One group read with a simulated gaze-contingent central scotoma while the other group served as a control group (Table 4.1).

The corpus of sentences used was corpus A, from (Albregues et al., 2019), consisting in 304 pairs of sentences. Each participant read one sentence from each pair, reading 304 sentences in total across two in-lab sessions.

Both groups performed the experiment while their eye movements were recorded by an eye tracker. For each target word, we recorded reading time, average fixation duration and fixation count.

	Self-Paced reading	Sentence corpus	Experimental setup	Outcome measures
Healthy young adults				
Control	N = 13 (6F / 7M) Mean age = 24.3 ± 1.8	Corpus #1 <i>304 sentences</i>	Computer screen + eye tracker	Reading time Fixation number Fixation duration
Simulated scotoma	N = 22 (15F / 7M) Mean age = 22.7 ± 2.4			

Table 4.1. Summary of experimental groups and conditions included in this study, as well as the corpus, experimental setup and outcome measures. In the scotoma group, 5 participants who did not reach a learning plateau (see Chapter 2 Section 6.1.2 for details) were not included in this study.

3 Results

3.1 Analysis 1 – Effect of orthographic similarity on reading time: two separate models

First, we fitted two separate linear mixed-effects models to examine the effect of orthographic similarity on word reading time, using Coltheart’s N (Model 1A) and OLD20 (Model 1B) as predictors. Both models included the same set of control predictors—word frequency, word length, in-context predictability, maximum neighbor frequency—and their interactions with scotoma condition and block number. Results from Models 1A and 1B are summarized in Table 4.2 and illustrated in Figure 4.2.

3.1.1 Model 1A – Coltheart’s N

In the control group, during block 1, the average reading times were identical for words with low N (few neighbors) and high N (many neighbors): 0.59 sec (Figure 4.2a). These results indicate no effect of neighborhood size on word reading time in the control group. As the experiment progressed, reading times decreased across blocks, reflecting a practice effect: from 0.59 sec in block 1 to 0.36 sec in block 19 for low-N words ($t=2.78$ for the block and control interaction effect), and an identical decrease for high-N words. In addition, the interaction between N and block in the control group was not significant, indicating that there was still no impact of N on reading time with practice in the control group ($t = 1.97$).

In the scotoma group, reading times were significantly longer. In block 1, words with low-N took 1.98 sec compared to 0.59 sec in controls ($t = -15.81$ - Figure 4.2a). Within the scotoma group, a higher N was associated with slower reading times during block 1: low-N words averaged 1.98 sec, compared to 2.32 sec for high-N words ($t = 5.06$; 17% increase). Reading times decreased across blocks, reflecting a significant practice effect (from 1.98 sec to 1.15 sec for low similarity, $t = -33.49$, and from 2.32 sec to 1.22 sec for high similarity). Importantly, the amplitude of the neighborhood effect decreased over practice ($t = -2.07$), from a 17 % slowdown in block 1 to 6 % in block 19.

Overall, Model 1 shows that Coltheart’s N influenced reading time solely in the presence of a simulated scotoma, with a stronger effect at the beginning of the experiment that decreased as participants gained practice.

Other fixed effects showed consistent influences on reading time. Higher word frequency and greater predictability were associated with shorter reading times (respectively, $t = -21.18$ and $t = -25.61$), while longer words and words with a highly frequent neighbor were read more slowly (respectively, $t = 3.10$ and $t = 3.57$).

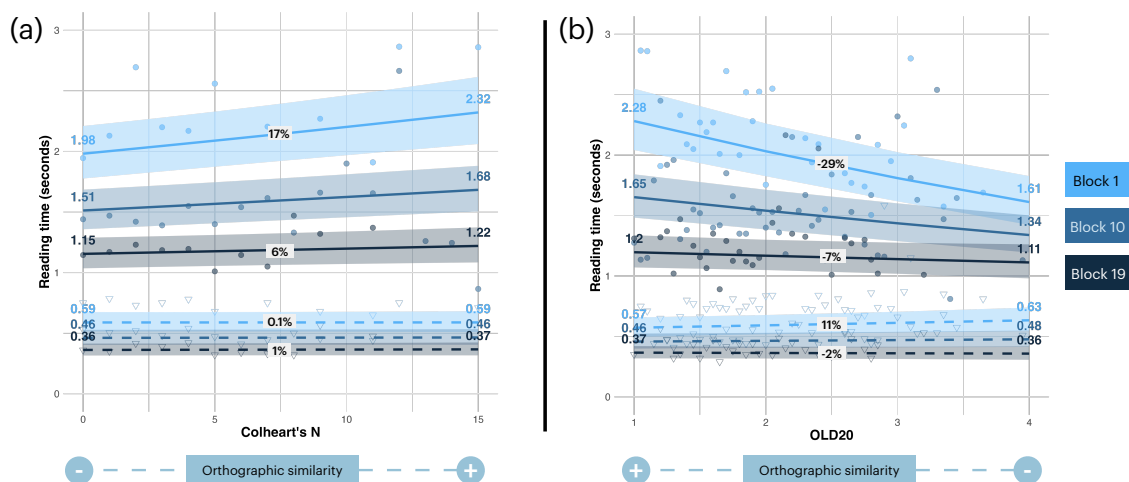


Figure 4.2 Relationship between word reading time and orthographic similarity, plotted for the scotoma group (solid lines) and the control group (dashed lines), and for three representative blocks (block 1 in light blue, block 10 in medium blue, block 19 in dark blue). (a) Model 1A using Coltheart’s N as the similarity metric. (b) Model 1B using OLD20. Points represent mean reading times for each value of N or OLD20, with filled circles for the scotoma group and open triangles for the control group. Lines are model-predicted slopes with shaded 95% confidence intervals.

Predictors	Model 1A - N		Model 1B - OLD20		Model 2 - both	
	Est.	t-value	Est.	t-value	Est.	t-value
(Intercept)	0.82	13.97	0.94	15.99	0.94	14.91
logfreq	-0.05	-21.18	-0.05	-21.36	-0.05	-21.49
nbcarr mot	0.01	3.10	0.01	4.64	0.01	4.59
block	-0.03	-33.49	-0.04	-25.65	-0.04	-14.87
control	-1.34	-15.81	-1.49	-17.38	-1.53	-17.11
pred	-0.44	-25.61	-0.43	-25.06	-0.43	-25.18
log MaxNF	0.01	3.57	0.01	3.69	0.01	3.55
block × control	0,003	2.78	0.01	6.67	0.02	5.45
logfreq × control	0.03	14.04	0.04	14.52	0.04	14.58
nbcarr mot × control	4e ⁻³	1.36	-2e ⁻³	-1.31	-5e ⁻³	-1.28
control × pred	0.32	16.05	0.30	15.34	0.30	15.35
control × log MaxNF	-0.01	-1.90	-0.01	-1.90	-0.01	-1.89
N	0.01	5.06			8e ⁻⁴	0.28
N × block	-4e ⁻⁴	-2.07			3e ⁻⁴	1.12
N × control	-0.01	-4.28			5e ⁻³	1.47
(N × block) × control	4e ⁻⁴	1.97			-7e ⁻⁴	-2.18
old20			-0.12	-7.23	-0.11	-5.17
old20 × block			0.01	3.76	0.01	3.41
old20 × control			0.15	8.11	0.18	7.01
(old20 × block) × control			-0.01	-4.64	-0.01	-4.76

Table 4.2. Fixed effect estimates from Model 1A, Model 1B and Model 2. Orthographic similarity is quantified with Coltheart's N in Model 1A, OLD20 in Model 1B and both in Model 2. The dependent variable is log-transformed word reading time. Interactions are represented by the symbol "×". Statistically significant predictors are shown in bold. CI = 95% confidence interval. Factors showing a significant effect on reading time are in bold font.

3.1.2 Model 1B – Orthographic Levenshtein Distance (OLD20)

When orthographic similarity was measured with OLD20 (Model 1B), the scotoma group displayed a very similar pattern as to what has been seen in Model 1A with N. In block 1 and with a scotoma, words with lower OLD20 (greater similarity) were read more slowly than those with high OLD20 ($t = -7.23$): 2.28 sec versus 1.61 sec, representing a 29% slowdown (Figure 4.2b). This effect of orthographic similarity weakened over blocks ($t = 3.76$), with reading falling from 1.2 sec (OLD20 = 1) to 1.11 sec (OLD20 = 4) in block 19, representing a 7% slowdown.

In the control group, the effect of OLD20 was smaller and reversed in direction (OLD20 × control: $t = 8.11$): in block 1, highly similar words (low OLD20) were read faster than less similar ones (0.57 sec vs 0.63 sec, 11% increase in reading time for high OLD20), and this advantage slowly decreased across blocks (block 19: 0.37 sec vs 0.36 sec, -2%). As in Model 1A, the control group was consistently faster than the scotoma group ($t = -17.38$), and both groups exhibited robust practice effects (main effect: $t = -25.65$ and in controls: $t = 6.67$).

As for Model 1A, an effect was also observed for other predictors from the model (Table 4.2): high-frequency and highly predictable words were read faster (respectively, $t = -21.36$ and $t = -25.06$), longer words and words with a highly frequent neighbor were slower (respectively, $t = 4.64$ and $t = 3.69$).

In both models, we found orthographic similarity to have an inhibitory effect on reading time when reading with a simulated central scotoma: reading time is longer when the orthographic similarity is high. In controls, the effect of orthographic similarity is either null or facilitative. In both groups, the amplitude of the effect of orthographic similarity decreases over the course of the experiment. The general impact of N and OLD20 on reading time with a simulated scotoma is quite comparable. However, a comparison of both models reveals a slightly smaller AIC and BIC for Model 1B, indicating a better fit.

3.2 Analysis 2 – Effect of orthographic similarity on reading time: a single model

To confirm that the separate models in Analysis 1 favor OLD20 over N, we fitted a single linear mixed-effects model (Model 2, Table 4.2) including both Coltheart's N and OLD20 as fixed effects, along with the same set of control predictors. This competition approach tested whether either measure accounted for unique variance in reading time when the other was present. We checked for multicollinearity and confirmed that both variables could be included in the same model. This 'competition' approach - fitting Coltheart's N and OLD20 in the same model to test for their unique contributions - has been used previously in the original introduction of OLD20 (Yarkoni et al., 2008).

3.2.1 Model 2 – N and OLD20

In this combined model, OLD20 remained a strong predictor ($t = -5.17$). In the scotoma group, words with low OLD20 were read more slowly in block 1 (2.27 s) than words with high OLD20 (1.62 s), representing a 29 % slowdown (Figure 4.3b). With practice, reading times decreased to 1.16 s (low OLD20) and 1.19 s (high OLD20), reducing the difference to 3 %, with an inverted slope ($t = 3.41$). In the control group, the OLD20 slope was smaller and reversed ($t = 7.01$): in block 1, words with low OLD20 were read slower than words with high OLD20 (0.56 s vs. 0.67 s, representing a 21 % slowdown), with the difference shrinking across blocks (0.37 s vs 0.35 s, 5 % slowdown by block 19, $t = -4.76$). And as in Model 1A and 1B, the control group was consistently faster than the scotoma group ($t = -17.11$), and both groups exhibited robust practice effects (main effect: $t = -14.87$ and in controls: $t = 5.45$).

By contrast, Coltheart's N no longer showed a significant main effect ($t = 0.28$), and its interactions with block and scotoma condition were non-significant or weak (N x block: $t = 1.12$; N x control: $t = 1.47$; three-way interaction: $t = -2.18$). In both groups, the N slopes in Figure 4.3a were nearly flat: in the scotoma group and in block 1, words with low N were read in 2.05 sec and 2.08 sec for words with high N, with similarly small differences in block 19

(1.15 sec vs. 1.26 sec). The control group also showed minimal differences across N levels (0.58 sec to 0.63 sec in block 1 and 0.36 across block 19).

Other fixed effects replicated the patterns of Analysis 1: higher frequency and greater predictability facilitated faster reading (respectively, $t = -21.49$ and $t = -25.18$), longer words and words with high frequency neighbors slowed reading (respectively, $t = 4.59$ and $t = 3.55$), and both groups improved with practice ($t = 14.87$).

Overall, Model 2 shows that when both measures are entered together in the same model, OLD20 remains a robust predictor of reading time when reading with a simulated scotoma, whereas Coltheart's N adds very little unique explanatory power beyond OLD20. For that reason, we decided to use OLD20 in further analyses.

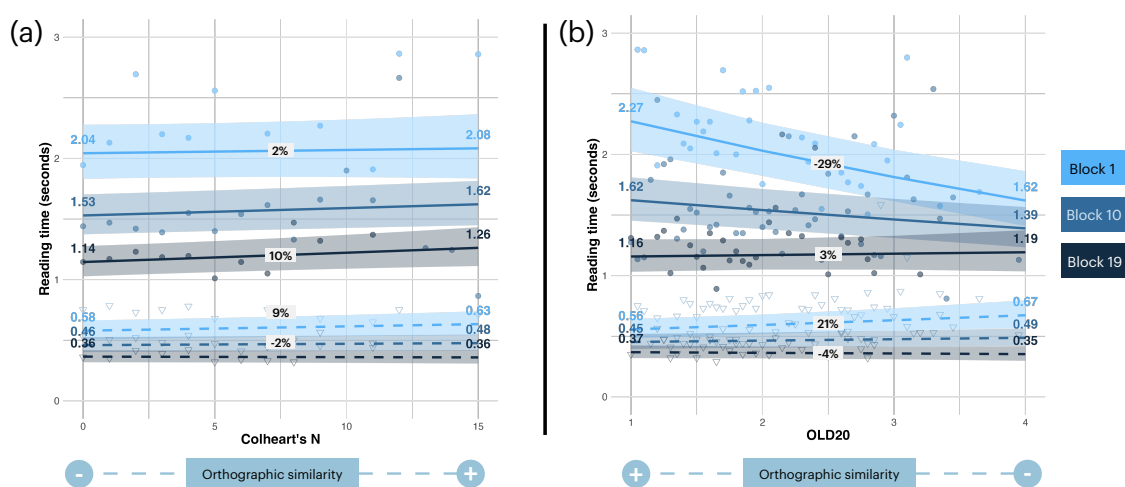


Figure 4.3 Relationship between word reading time and orthographic similarity for the scotoma group (solid lines) and the control group (dashed lines), and for three representative blocks (block 1 in light blue, block 10 in medium blue, block 19 in dark blue). (a) Effect of Coltheart's N on reading time. (b) Effect of OLD20 on reading time. Both plots are outputs from Model 2. Points represent mean reading times for each value of N or OLD20, with filled circles for the scotoma group and open triangles for the control group. Lines are model-predicted slopes with shaded 95% confidence intervals.

3.3 Analysis 3 – effect of orthographic similarity on oculo-motor pattern

To further investigate the mechanisms underlying the effect of OLD20 on reading time observed in Model 1B, we examined whether these changes were driven primarily by differences in fixation duration or by differences in the number of fixations per word, or both. Two separate linear mixed-effects models were fitted: Model 3A predicted the average fixation duration per word, and Model 3B predicted the fixation count per word, with OLD20 as the main predictor and the same control predictors used in previous analyses (word frequency, word length, predictability, maximum neighbor frequency, block number, and group).

3.3.1 Model 3A - Fixation duration

In the first block of the experiment, increasing OLD20 in the scotoma group was associated with a significant 8 % decrease in fixation duration (from 239 ms to 220 ms; $t = -2.85$, Figure 4.4). In other words, more similar words (low OLD20) elicited longer fixations, consistent with the reading time results in Models 1B and 2 . With practice, this relationship flattened and even reversed to become slightly positive: by block 19, fixation duration rose a little as OLD20 increased (from 213 ms to 222 ms; $t = 2.72$). This second result also aligns with the effect of OLD20 on reading time. However, unlike for reading time, the average fixation duration was similar in the two groups (scotoma vs. controls; $t = -0.51$).

In the control group, fixation duration was not related to OLD20, with a near-flat slope in the first block (from 208 ms for low OLD20 to 211 ms for high OLD20; $t = 0.40$). The slope in block 19 appeared steeper but was not significant in the model ($t = -0.31$), most likely due to the overlap of the confidence intervals.

Overall, the effect of OLD20 on fixation duration shows only modest resemblance to its effect on reading time, described in Analyses 1 and 2.

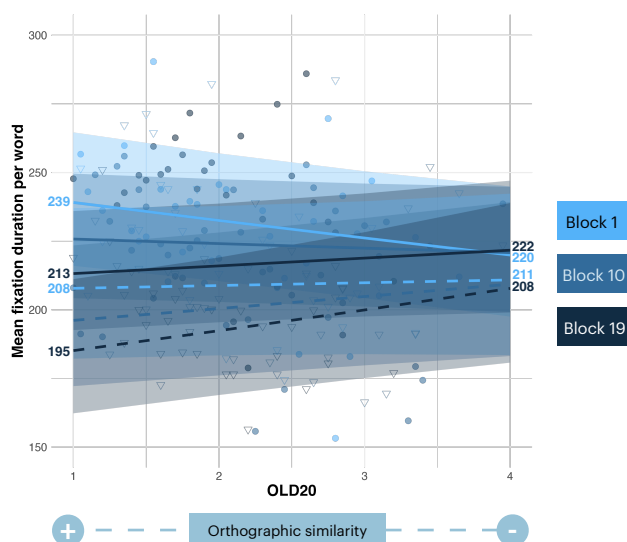


Figure 4.4 Mean fixation duration per word, as a function of orthographic Levenshtein's distance, grouped by condition and block number. Data points show fixation duration for each value of OLD20, broken down by condition (scotoma in filled circles vs. control in open triangles) and block index (light blue for the first block, up to dark blue for the last block). Lines represent slopes estimated by Model 3B, along with their 95% confidence intervals (solid lines for the scotoma group; dashed lines for the control group).

3.3.2 Model 3B – Fixation number

In contrast with fixation duration, fixation count showed a strong and systematic relationship with OLD20, that closely paralleled the reading time patterns reported in Model 1B (Figure 4.5). In the scotoma group, increasing OLD20 was associated with a significant decrease in fixation number ($t = -6.62$): words with low OLD20 (i.e., more visually similar neighbors) elicited more fixations than words with high OLD20 (6.6 vs. 4.8 fixations on average, representing a 26 % decrease). Across blocks, fixation counts significantly decreased with practice ($t = -9.27$), but the OLD20 effect remained significant ($t = -2.66$), indicating that even after training, visually similar words continued to require more fixations (3.4 vs. 3 fixations in block 19 on average, representing an 11% difference).

In the control group, the pattern was reversed: in block 1, fixation number increased with OLD20 (1.5 vs. 1.8 fixations, 21% increase; $t = 2.81$), meaning that less similar words tended to trigger more fixations in normal viewing. This difference diminished across blocks (1.1 vs. 1 fixations in block 19, $t = 4.01$).

Overall, Model 3B shows that the influence of OLD20 on reading time (Model 1B) closely mirrors its effect on fixation count. Taken together, these results indicate that the impact of OLD20 on reading time under simulated scotoma is primarily driven by changes in fixation count rather than fixation duration (see resemblance between Figure 4.2b and Figure 4.5). In other words, the longer reading times observed in Model 1B were mainly due to an increased number of fixations per word.

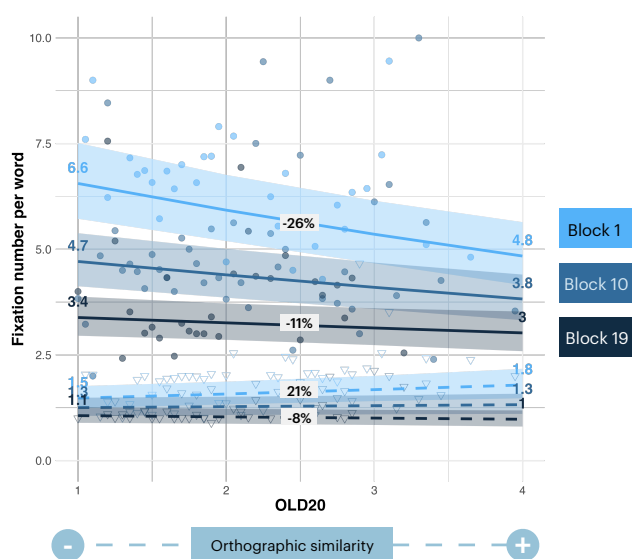


Figure 4.5 Mean fixation count per word, as a function of orthographic Levenshtein's distance, grouped by condition and block number. Data points show fixation count for each value of OLD20, broken down by condition (scotoma in filled circles vs. control in open triangles) and block number (light blue for the first block, up to dark blue for the last block). Lines represent slopes estimated by Model 3B, along with their 95% confidence intervals (solid lines for the scotoma group; dashed lines for the control group).

4 Discussion

Neighborhood size (N)

The first goal of the present chapter was to investigate the influence of orthographic similarity when reading with eccentric vision. As already described, both the neighborhood size (Coltheart's N) and the Orthographic Levenshtein Distance 20 (OLD20) have been used as efficient measures of orthographic similarity in normal reading. However, in the specific context of CVL, only N has been investigated before (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a).

To build up on previous results and allow valid comparisons, we first investigated how word neighborhood size (N) affects reading time in individuals with simulated central scotoma. Our results show that words with a large neighborhood size elicit longer reading time than words with a smaller neighborhood. This finding contrasts with previous research in readers with normal vision, for whom lexical access is facilitated by larger neighborhood sizes (for reviews, see (Andrews, 1997) and (Perea & Rosa Martínez, 2000)). However, our results align with previous research on neighborhood size in patients with CVL (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). With a central scotoma, visual

degradation and text occlusion make it harder to distinguish words from one another. Consequently, a large orthographic neighborhood increases ambiguity, hence difficulty, and yields longer reading time in patients with CVL (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). The present study successfully replicated these effects when reading with eccentric vision (Model 1A).

Moreover, results from actual patients revealed that the negative influence of the neighborhood size on reading time only applied to patients who had quit reading on a daily basis, suggesting that the influence of orthographic similarity on reading depends on the amount of reading practice (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). Again, our results from healthy readers forced to read with eccentric vision do align with these results. At the start of our experiment, participants in the simulated scotoma group, who were not yet used to read with a central scotoma, exhibited longer reading time for words with more orthographic neighbors, revealing a strong inhibitory effect of neighborhood size. By the end of training, however, this effect became minimal, just as in the patients tested by Sauvan and collaborators who still read daily. Hence, the different effects obtained in our participants before and after training may be assimilated to the different results yield by patients' reading status (daily readers vs. individuals who quit reading).

We conclude that enforcing visual rehabilitation and daily practice of reading for patients with acquired CVL should reduce the negative influence of words with large neighborhood size. A similar conclusion was already drawn in the context of predictability effects (Chapter 3). Finally, being able to reproduce results from pathological readers in healthy individuals supports the use of a simulated scotoma to study pathological reading with CVL.

N vs OLD20

The second goal of this chapter was to identify the orthographic similarity measure that best predicts changes in reading time when reading with eccentric vision: N vs. OLD20. Our main hypothesis was that the Orthographic Levenshtein Distance (OLD20), a more sensitive measure of orthographic similarity than the traditional neighborhood size (N), would better explain the variability in reading time observed in the presence of a simulated scotoma. Additionally, OLD20 has been increasingly used in research on visual word recognition (see Perea, 2015 for a review). When modeling reading time with OLD20 as a predictor (Model 1B), the results paralleled those obtained with neighborhood size: before training, higher OLD20 values - indicating less similar neighbors - were associated with shorter reading times. By the end of the training, OLD20's impact on reading time significantly diminished.

In both Model 1A and Model 1B, the impact of orthographic similarity was stronger when participants were not yet accustomed to the scotoma simulator. These results align with those of Sauvan and collaborators, who found N to have a strong impact on patients with CVL without reading practice as they had stopped reading daily. Results from OLD20 confirm that orthographic similarity is especially relevant during the early stages of reading rehabilitation in CVL.

Both models reflect an effect of orthographic similarity on reading that is specific to eccentric vision, since (1) the effects appear both in pathological CVL reading and simulated CVL reading but differ from controls, and (2) the impact of N or OLD20 was comparable in both groups. To compare the two models, we conducted a likelihood ratio test using the `anova()` comparison function in R, which revealed no significant difference, and both were equally parsimonious. However, the model including OLD20 had a lower Akaike Information Criterion (AIC), suggesting a better fit.

To confirm that OLD20 was indeed a better predictor, we created a model including both measures (Analysis 2, Model 2). In this combined model, the effect of neighborhood size weakened, while the effect of OLD20 remained strongly significant (Figure 4.3). This provides robust support to conclude that OLD20 is a superior indicator of changes in reading time among young adults reading with eccentric vision. These findings are consistent with the dual-route model of orthographic processing (Grainger & Ziegler, 2011), which posits that visual word recognition can proceed through a fast, coarse-grained route that relies on approximate letter order and global shape cues, or a slower, fine-grained route that encodes precise letter identities and positions. Under suboptimal visual conditions, coarse cues become less reliable, and processing shifts toward the fine-grained route. Because this route demands detailed letter-by-letter discrimination, it is particularly vulnerable to interference from highly similar lexical candidates - precisely the type of competition captured by low OLD20 values.

Future studies with CVL patients should help determine whether the advantage of OLD20 over N holds in the clinical population. However, this will not be done in the context of this thesis, as we chose to use OLD20 (rather than N) when investigating orthographic similarity effects in patients with CVL (see Chapter 6).

Maximum neighbor frequency (MaxNF)

In addition to N and OLD20, we examined the impact of neighbors' frequency on reading time. In the literature, the most studied measure captures the presence of at least one higher-frequency neighbor (HFN). Previous eye-movement studies have shown strong competition between a target and its higher-frequency neighbor, with the effect modulated by sentence context (Slattery, 2009). This inhibitory effect has been replicated across strict substitution neighbors (Acha & Perea, 2008; Johnson, 2009) as well as letter additions and deletions (Davis et al., 2009).

We computed the HFN variable (coded 1 = one higher frequency neighbor and 0 = none) based on the OLD20 neighborhood set – an approach that, to our knowledge, has not been implemented before. In our Model 1B, we did not find any significant competition effect in either population (with or without a simulated central scotoma). This null result is likely related to the self-paced reading procedure, which produces relatively long and segmented reading time, potentially masking the fine-grained lexical competition effects typically observed in natural reading paradigms.

We also computed the maximum neighbor frequency (MaxNF), defined as the frequency of the most frequent neighbor. When examining the MaxNF, we observed a significant effect in the scotoma group (Table 4.2). Words whose most frequent neighbor had a high frequency were read more slowly, suggesting stronger lexical competition under degraded visual input.

Frequency x similarity reversal

Neighborhood size has also been studied in relation to word frequency. In normal readers, Lim (2016) reported facilitatory effects of both frequency and neighborhood density, with a stronger neighborhood effect for low-frequency words (Lim, 2016). In contrast, we observed the opposite pattern: the interaction between OLD20 and frequency was stronger for high-frequency words. Frequency measures were comparable across studies, but Lim used neighborhood size (N), whereas we used OLD20. It is possible that OLD20 and N interact differently with frequency. Moreover, Lim's study used a lexical decision task, whereas our participants read sentences aloud. These methodological differences could explain why we observed a reversal of the interaction compared to Lim (2016). Further research is needed to establish whether this effect is specific to eccentric reading or whether it is task dependent.

Predictability

Beyond orthographic similarity, our model also revealed a robust effect of predictability on reading time in both groups. As discussed in Chapter 3, predictability is one of the strongest linguistic influences on reading in the general population (Rayner et al., 2006). In the present study, its effect under simulated scotoma was considerably stronger. This finding is consistent with what we reported in Chapter 3, despite the use of a different data set in the present analysis. Indeed, even though both data sets came from a single experiment, they differ in several manner. First, the present analysis used almost all words from a sentence (see Chapter 2 Section Chapter 25 for details), whereas the analysis presented in Chapter 3 used a single target word per sentence. Second, in-context predictability was estimated with two different methods in both studies (as explained in details in Chapter 2 Section 5.2.5), yielding different values of predictability. Consistency in the predictability effect we report confirms that predictability should be carefully considered in reading-based rehabilitation for CVL, particularly in the early stages of training.

Word length control

Experiments investigating orthographic neighbors often restrict word length to a narrow range, since shorter words tend to have more neighbors and longer words tend to have very few. Following Andrews' recommendation, we excluded words shorter than 4 letters (Andrews, 1997). However, we chose to include longer words, since OLD20 distributions were stable for words between 4 and 13 letters, while N distributions were consistent only for words up to 9 letters. This methodological consideration also highlights the advantage of using OLD20 over N.

5 Conclusion

In conclusion, this study demonstrated that orthographic similarity affects reading under simulated central scotoma and that practice reduces this influence as readers adapt to eccentric vision. We further showed that OLD20 provides a more reliable measure of orthographic similarity than neighborhood size (N), and that predictability has a particularly strong effect when central vision is impaired. Accordingly, we will use OLD20 as the orthographic similarity metric in subsequent analyses in this manuscript (Chapter 6) and will no longer report Coltheart's N. Taken together, these findings highlight the dual importance of word-level similarity and contextual support in shaping reading under visual impairment. Our results support the hypothesis that reading strategies adapt with peripheral vision training (or simulated scotoma training), reducing the disruptive influence of orthographic neighbors as readers develop more efficient compensatory mechanisms.

Still, the findings reported in this chapter may not be universally applicable, as the influence of linguistic factors evolves with age due to shifts in reading strategies (Kliegl et al., 2004a; Rayner et al., 2006). Our results therefore might differ in older adults, who represent the population most affected by central vision loss. Future work will test whether the same patterns hold in this group (Chapter 6) and investigate how compensatory reading strategies emerge over time (Chapter 7).

**Part III – Bridging the gap between
psycholinguistic complexity and
visual ambiguity when reading with
eccentric vision**

Chapter 5 MEASURING VISUAL AMBIGUITY IN WORDS: DEVELOPMENT AND VALIDATION OF TWO NEW METRICS

In Chapter 5, I introduced two new metrics to quantify the visual ambiguity of words when reading with central vision loss: the Word Ambiguity Measure (WAM) and VA20.

These measures are based on the visual overlap between letters and words, rather than on spelling distance alone, capturing confusability at the pixel level. The goal was to address a limitation of classical orthographic metrics (e.g. OLD20) that ignore actual letter shape similarity.

Using data from young adult readers, I showed that WAM and VA20 predict reading performance independently of lexical factors like word frequency and predictability.

This finding reinforces the impact of a word’s visual appearance in eccentric reading and motivates the integration of measure accounting for both visual and psycholinguistic aspects of text.

Together, WAM and VA20 provide a systematic way to quantify visual confusability in text. By bridging visual psychophysics and psycholinguistics, Chapter 5 contributes a new methodological tool for assessing how visual factors constrain reading, thereby enriching our understanding of reading adaptation under central vision loss.

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1 Introduction

Ambiguity is the quality of being open to more than one interpretation. For an image, ambiguity occurs when visual elements can be understood in two or more distinct ways, which may cause confusion, as illustrated in Figure 5.1. Applied to the field of typography, ambiguity refers to the potential for visual uncertainty in how characters are perceived and interpreted by viewers (Lupton, 2010). This can arise from factors such as: layout or spacing (e.g., ambiguous word breaks); legibility issues (e.g., poor contrast, small print size) or characters similarity itself (e.g., confusion between "l" and "t" or "O" and "0") (Bigelow, 2019).



Figure 5.1. Several interpretations from an ambiguous image. The first image can be interpreted in three ways: as the letters "K B", as the letters "VD" with their mirror image, or as the mathematical inequality " $1 < 13$ " (Modified from (Postic et al., 2017)).

Within a legible font, characters similarity has a negligible influence on reading performance when reading with central vision, where acuity is at its best (Bouma, 1971). On the other hand, when reading words with eccentric vision, the visual ambiguity yield by the presence of letters that share similar features with other characters, have a strong impact on letter identification (Coates et al., 2019) and may in turn slow down reading speed.

It has already been shown that reading under degraded visual conditions can be hindered by the perceptual similarity of different letters or words. For example, in low contrast or blurred text, the letters "c" and "o" or "r" and "n" may become difficult to distinguish. Such visual confusability has long been recognized as a limiting factor in letter and word recognition (Bouma, 1971; Pelli et al., 2006), and its impact can be exacerbated by crowding effects in peripheral vision (Levi, 2008; Pelli & Tillman, 2008). Under these conditions, letter recognition errors are more likely when letters share similar visual features, as shown in studies of letter identification via substitution errors (Gilmore et al., 1979; Podgorny & Garner, 1979).

In previous chapters, we have investigated the influence of well-defined psycholinguistic factors, such as in-context predictability (Chapter 3) and orthographic similarity (Chapter 4), when reading with eccentric vision. In addition, we believe that visual ambiguity should not be overlooked in the investigation of reading with eccentric vision. Therefore, the present chapter is dedicated to the development and validation of two new metrics designed to measure visual ambiguity in words.

To start with, we will present the general methodology we developed to compare characters shape: a font-specific pixel-overlap procedure to quantify visual similarity between character strings. Then we will present the two different measures envisioned throughout this thesis

that were derived from our methodology. First, we will describe the Word visual Ambiguity Measure (WAM), which gives for each single word its level of visual ambiguity based on the letters it is composed of. Second, we will detail the new measure Visual Ambiguity 20 (VA20), an extension of OLD20, that takes into account the physical letter resemblance between neighbors, providing a visually grounded measure of orthographic similarity.

2 Methods

Our goal was to create a method to determine how visually similar a character string is to another string in a given font. Such measure should reflect the degree to which a string (e.g., single letter, word) could be confused with others based purely on its physical form.

While letter similarity can be estimated in multiple ways — for example, by analyzing perceptual confusions in behavioral tasks (Gilmore et al., 1979) or by measuring the empirical impact of letter features overlap (Podgorny & Garner, 1979) — our goal was to create a method that was (a) directly tied to the font used in our experiment (i.e., Courier New), and (b) grounded in the visual rendering of text that participants actually saw. Importantly, we wanted to design a method that could easily be applied to any given font.

We chose a pixel-overlap approach, which quantifies similarity based on the proportion of shared pixels between two rendered string images. This choice was motivated by previous work showing that typographic variables such as stroke width, x-height, and serif design can substantially affect letter recognition (M. Bernard et al., 2002; Mansfield et al., 1996). By making the computation font-specific, we: (1) ensured that the resulting scores captured the true confusability for the actual text style used in the study, rather than assuming a generic letter shape; (2) allowed for an automated calculation in any given font.

To estimate a measure of visual similarity between two strings, we designed an automated routine, based on image processing and developed in R using custom-made functions. This routine, detailed below, will be referred to as the “sliding-window pixel-overlap” method:

- (1) Both strings of a comparison are rendered as an image in a given font (Courier New in the example below);
- (2) The “target” image (in black in Figure 5.2) is kept stationary;
- (3) The “moving” image (in red in Figure 5.2) is first positioned to the left of the target and then shifted horizontally to the right, one pixel at a time, until it is positioned to the right of the target image;
- (4) For each pixel shift (i.e., each given position of the moving image), we computed the proportion of overlapping pixels the two images share, relative to the total pixel area (in percent);
- (5) For each string comparison the percentage of pixel overlap were plotted as a function of shift size, to obtain an overlap profile (Figure 5.3).
- (6) For each profile, we chose the value of the highest peak, throughout the whole profile, as our measure of visual similarity.

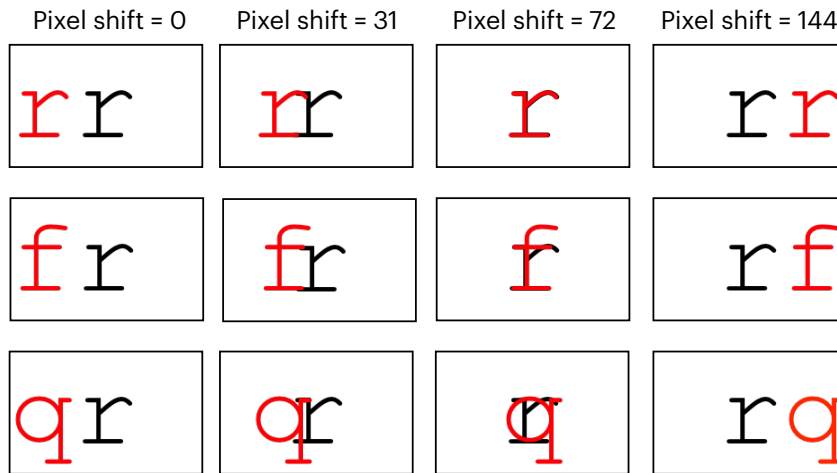


Figure 5.2. Examples of three different pairwise letter-shape comparisons. The black letter “r” is the fixed target, and the red letter is the moving letter - either “r” (top row), “f” (second row) or “q” (bottom row). Across columns, the comparison letter is horizontally shifted by increasing the pixel offset from left to right, illustrating how overlap changes with shift amplitude.

While we also considered using the area under the curve, representing the total amount of overlap occurring between two letters, this value did not reflect the perfect match occurring between two identical strings. On the other end, the peak value provided a perfect score of 1 for identical strings, making it the best candidate to score visual ambiguity between two given strings. This peak score ranged from 0 (minimal similarity) to 1 (identical shapes). For example, in Courier New, comparison between the letters “r” and “r” obtained a score of 1, while the letters “r” and “f” achieved a peak overlap of 0.61, and the letters “r” and “q” a score of 0.26 (Figure 5.3).

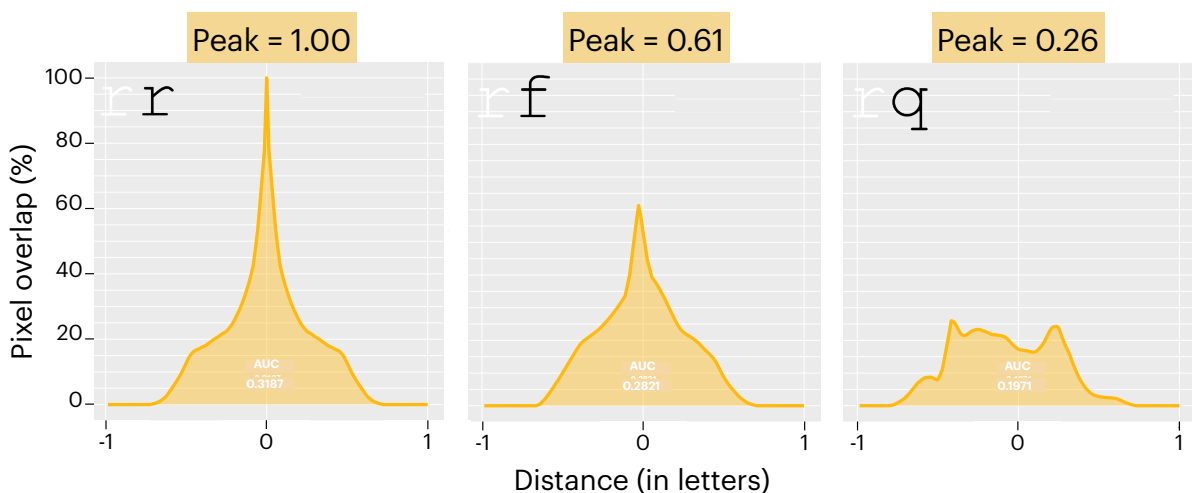


Figure 5.3. Overlapping profile of letters two by two. “r” and “r” have the highest possible maximum peak overlap (100%), and “r” and “f” have a higher maximum peak overlap (61%) compared to “r” and “q” (26%).

3 Word visual Ambiguity Measure (WAM)

The Word visual Ambiguity Measure (WAM) is a font-specific metric designed to quantify the degree to which a word’s visual form might lead to misidentification. WAM is grounded in the idea that both individual letters and adjacent letter pairs (bigrams) can vary in their level of visual confusion, depending on the visual rendering of the text.

For instance, consider the French synonyms *utiliser* (“to use”) and *employer* (“to employ”). The first occurs far more frequently in text (62.82 occurrences per million) than the second (4.21 occurrences per million), yet its visual form is arguably more ambiguous: sequences such as “t-i-l-i” contain several visually similar letters, while in *employer*, the distinct shapes of “p”, “l”, and “y” could reduce ambiguity and facilitate word identification. This contrast illustrates how visual factors may partly offset or modulate frequency effects – especially in visually impaired readers – and motivates the development of a quantitative measure of visual ambiguity at the word level.

Our motivation, when designing this measure, was to estimate, for each given word, a measure of its overall visual ambiguity, based on the sequence of letters it is composed of. To do so, we distinguished two different sources of ambiguity:

- Ambiguity at the letter level: the ambiguity between a letter on the screen and any other potential letter from the alphabet, taking into account that some letters may share a lot of features with others (e.g., “o” or “a”), making them easily confusable; while some letters share few features with other characters (e.g., “x” or “w”), making them easier to distinguish;
- Ambiguity at the bigram level: the ambiguity between two letters that are actually on the screen and that could be misidentified for one another.

Below we present in detail how WAM is computed. First, we describe how visual ambiguity scores were computed for single letters of the alphabet (letter-level ambiguity). Second, we present how a bigram visual ambiguity measure was derived for each possible pair of letters within a word. Third, we detail how the word-level integration was performed to obtain WAM.

3.1 Letter-level visual ambiguity

In this first step we computed a letter ambiguity score, to estimate how visually similar each letter is to every other letter in the target alphabet. This letter ambiguity score reflects the average degree to which a letter could be confused with any others based purely on its physical form.

For each letter, we ran a pairwise comparison with all other letters from the alphabet using the “sliding-window pixel-overlap” method. Below is the letter visual ambiguity matrix summarizing all the pairwise comparisons of the lowercase alphabet we computed in Courier New. Letters were ordered to highlight clusters of ambiguous characters, such as e-o-c, p-q-g, or f-l-r-i (Figure 5.4).

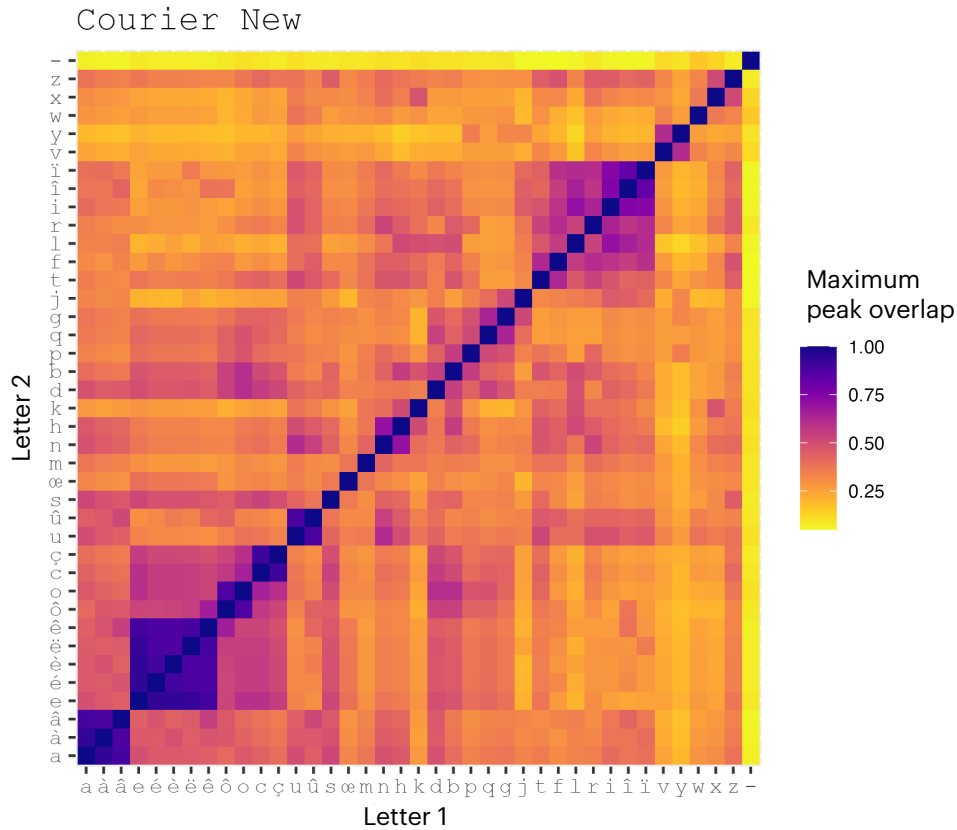


Figure 5.4. Letter visual ambiguity matrix for lowercase letters in Courier New. Each cell represents the maximum proportion of overlapping pixels between two letters, computed across all horizontal alignments. Darker shades indicate greater visual similarity – the diagonal dark purple equal to 1 (perfect match), and off-diagonal patterns reveal systematic clusters of visually similar letters. Here again, “r” and “f” are visually more similar than “r” and “q”.

Finally, for each letter, we computed its unique score of ambiguity, by summing the peak scores from all comparisons with the other letters from the alphabet, divided by the total number of comparisons. Values were scaled from 0 to 1 across the entire alphabet to make the score more “interpretable”: the highest score of 1 applies to the letter with many visually similar counterparts (e.g., “e”), while the lowest score of 0 indicates a distinctive letter (e.g., “y”) (Table 5.1).

Letter	Ambiguity score	Letter	Ambiguity score	Letter	Ambiguity score	Letter	Ambiguity score
e	1.000	n	0.862	z	0.693	j	0.383
a	0.950	t	0.821	p	0.668	x	0.352
d	0.929	s	0.810	q	0.628	w	0.216
b	0.917	i	0.808	g	0.617	v	0.193
o	0.914	r	0.804	l	0.588	y	0.000
c	0.913	h	0.782	m	0.507		
u	0.893	f	0.729	k	0.464		

Table 5.1. Ambiguity scores from 0 to 1 for each letter of the alphabet, sorted from highest values (letters with many visually similar counterparts) to lowest values (letters with a distinctive shape).

3.2 Bigram-level visual ambiguity

While individual letters can be confused based on their shapes, visual confusion can also arise from crowding. Using the peak overlap between each letter bigram, we can directly use this resource to assign ambiguity scores to each pair of adjacent letters within a word (e.g. for cat, we would consider the bigrams “ca” and “at”). The bigram ambiguity score for a word corresponds to the highest peak overlap score found in a word.

Table 5.2 provides an example for the two French synonyms “utiliser” and “employer”. The overall score of ambiguity derived from the bigrams is higher for the word “utiliser”, which contains several highly ambiguous bigrams (“li”, “il”) compared to the word “employer”, whose adjacent letters are more visually distinct.

By using the maximum bigram ambiguity score within a word as the overall score, we ensured that the score was not affected by the word length (i.e., number of bigrams), while also ensuring that the presence of a single ambiguous bigram was enough to drive the overall score up.

		utiliser							
Bigram		ut	ti	il	li	is	se	er	Overall score
Ambiguity score		0.522	0.482	0.704	0.704	0.328	0.524	0.307	0.704
		employer							
Bigram		em	mp	pl	lo	oy	ye	er	Overall score
Ambiguity score		0.298	0.346	0.261	0.216	0.198	0.207	0.307	0.346

Table 5.2. Bigram ambiguity measured for two different synonyms, “utiliser” and “employer”, in Courier New.

3.3 Word-level visual ambiguity measure (WAM)

Our first intention was to create a final WAM score that integrates the two components described above – letter-level ambiguity and bigram-level ambiguity – into a single value for each word. However, given the exploratory approach we took in creating this measure, we decided to compute several variants of WAM, to select the one that would better reflect word ambiguity. Here we will present only two of these variants: *WAM_letter* and *WAM_letter-bigram*.

WAM_letter was computed by averaging the letter ambiguity score of all the letters composing a word, as follows:

$$WAM_{letter} = \frac{e_1 + e_2 + \dots + e_n}{n} = \frac{1}{n} \sum_{i=1}^n e_i$$
 where n is the number of letters in the word and e_i is the letter ambiguity score of the letter i .

$WAM_{letter-bigram}$ was computed by multiplying WAM_{letter} with the overall bigram ambiguity of a word (as described above in Section 3.2), as follows:

$WAM_{letter-bigram} = WAM_{letter} \times B$ where the overall bigram ambiguity B is defined as the maximum bigram ambiguity score across all adjacent letter pairs.

This multiplicative combination ensures that a word receives a high score only if it contains both highly confusable letters and at least one strongly confusable letter pair, reflecting the joint contribution of letter and bigram-level similarity to visual ambiguity. Table 5.3 shows how both WAM_{letter} and $WAM_{letter-bigram}$ were computed for the word “utiliser”.

utiliser									
Letter	u	t	i	l	i	s	e	r	Mean Letter ambiguity
Ambiguity score	0.893	0.821	0.808	0.588	0.808	0.810	1.000	0.804	0.817
Bigram	ut	ti	il	li	is	se	er	--	Max bigram ambiguity
Ambiguity score	0.522	0.482	0.704	0.704	0.328	0.524	0.307	--	0.704
WAM_letter									0.817
WAM_letter-bigram									0.575 (0.817*0.704)

Table 5.3. Examples of letter-level ambiguity scores and bigram-level ambiguity (peak pixel overlap) for the word “utilise”. The letter ambiguity score is added up for each letter of the word, and its mean is computed as the mean letter ambiguity (0.817 here). Then, the bigram ambiguity score is added up for each adjacent letter duo of the word, and the highest bigram score of the word is chosen as the max bigram ambiguity (here 0.704). Then, two measures are extracted: WAM letter corresponds to the mean letter ambiguity computed in the first step (WAM letter = mean letter ambiguity = 0.817), and WAM letter-bigram corresponds to the product of mean letter ambiguity and max bigram ambiguity (WAM letter-bigram = mean letter ambiguity * max bigram ambiguity = 0.817* 0.704 = 0.575).

3.4 Experimental validation of WAM

In order to select an optimal variant of WAM and validate its efficiency in translating word visual ambiguity, we tested its influence on reading time using data collected in our group of young participants, both reading with and without a simulated scotoma with the self-paced reading paradigm (see Table 2.1).

First, we fitted a simple LME model using the log-transformed reading time of each word as the dependent variable and all the following variables as fixed factors: simulated scotoma (yes/no), log-transformed word frequency, word length, old20, word predictability and maximum neighbor frequency. This simple model yielded an adjusted R2 of 0.71, meaning

that all the factors included as fixed effects explained 71% of the overall variance in word reading time.

Then, for each variant of WAM, we created a more complex model by adding WAM as an additional fixed effect to the baseline structure described above. We assessed the contribution of WAM by comparing the two models (simple model vs. WAM model) using an ANOVA (likelihood ratio test).

3.4.1 Effect of WAM_letter-bigram on reading time

The WAM_letter-bigram model showed no significant difference from the baseline model (ANOVA likelihood ratio test: $p = 0.42$), suggesting that the addition of WAM_letter-bigram did not improve the model's ability to explain variance in word reading time. This was confirmed by the results of the WAM_letter-bigram model (Figure 5.5). WAM_letter-bigram had no significant effect on reading time in either the control ($t = -0.1$) or the simulated scotoma group ($t = 0.9$).

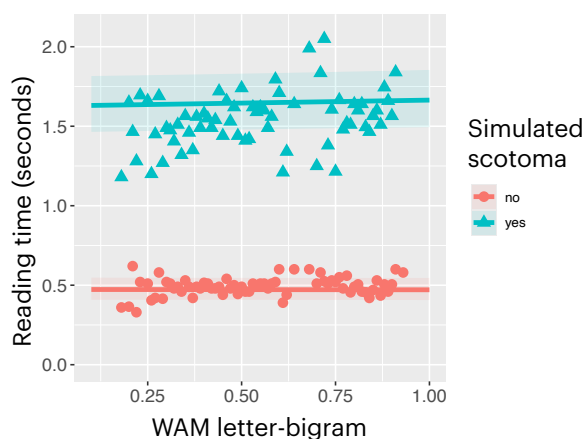


Figure 5.5 Reading time (s) as a function of letter and bigram-based visual ambiguity (WAM letter-bigram) for control (no simulated scotoma - red) and simulated scotoma (blue) conditions. Each data point corresponds to the mean reading time for observations grouped by WAM values within each condition. Higher WAM values indicate greater confusability. Linear fits show no significant relationship in either condition.

3.4.2 Effect of WAM_letter on reading time

The WAM_letter model differed significantly from the baseline model ($p < 0.001$), suggesting that the addition of WAM_letter help better explain changes in word reading time. The WAM_letter model obtained a smaller AIC, also indicating that the addition of WAM_letter was an improvement compared to the simple model.

This was confirmed by the results of the WAM_letter model (Figure 5.6). While WAM_letter showed no significant effect on reading time in the control group ($t = -0.6$, red line), it had a significant effect on the reading time in the simulated scotoma group ($t = 7.2$, blue line), increasing reading time from 1.34 seconds when $WAM = 0.5$ to 2.16 seconds when $WAM = 1$, which corresponds to a 62% increase in reading time.

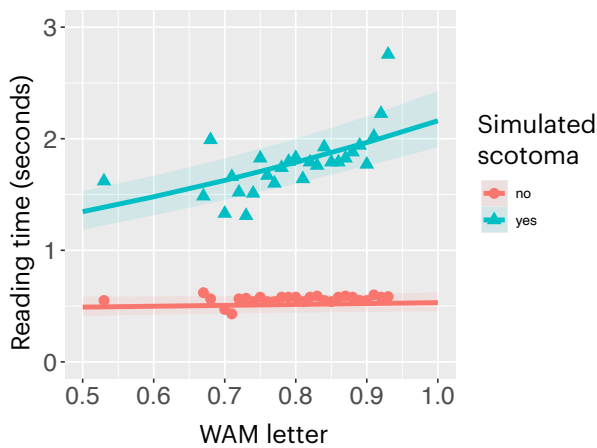


Figure 5.6 Reading time (s) as a function of letter-based visual ambiguity (WAM letter) for control (no simulated scotoma - red) and simulated scotoma (blue) conditions. Each data point corresponds to the mean reading time for observations grouped by WAM values within each condition. Higher WAM values indicate greater confusability. Linear fits shows a significant relationship in the scotoma group (blue).

3.5 Conclusion

The development of the Word visual Ambiguity Measure (WAM) aimed to quantify how the visual form of a word may contribute to reading difficulty, especially when reading with impaired or eccentric vision. The present analyses provide encouraging evidence that this goal was achieved. Among the different variants tested, WAM_letter – which integrates the intrinsic visual confusability of the letters composing a word – successfully predicted reading time under simulated CVL. Specifically, words composed of more visually confusable letters were read significantly more slowly when central vision was occluded. This pattern confirms that visual ambiguity becomes a limiting factor when letter identification relies on eccentric regions, validating the theoretical rationale behind the measure.

These results establish WAM_letter as a promising and sensitive metric for capturing the visual complexity of words at the perceptual level. By contrast, the combined variant WAM_letter-bigram, which additionally accounted for the most ambiguous letter pair within each word, did not significantly improve model fit. This suggests that the letter-level component already captures the bulk of the visual uncertainty relevant to reading under degraded viewing conditions. Nonetheless, the bigram-based extension remains conceptually valuable, as it may better reflect effects of crowding and inter-letter interference, which could emerge under different fonts or display conditions.

Looking ahead, several methodological refinements could further improve the WAM metric. We previously tested the area under the overlap curve (AUC - Figure 5.7 A) and found that it did not outperform the peak-based score. However, the peak-based approach may underestimate perceptual similarity in cases where letters have multiple partial alignments. As illustrated by the “n-m” pair (Figure 5.7 C), small positional offsets or local shape mismatches can reduce peak overlap despite strong perceptual confusability. Future versions of WAM could address this by incorporating a “between-peaks” AUC, integrating information across local maxima to capture near-alignments that are likely to produce confusions under eccentric viewing (Figure 5.7 B).

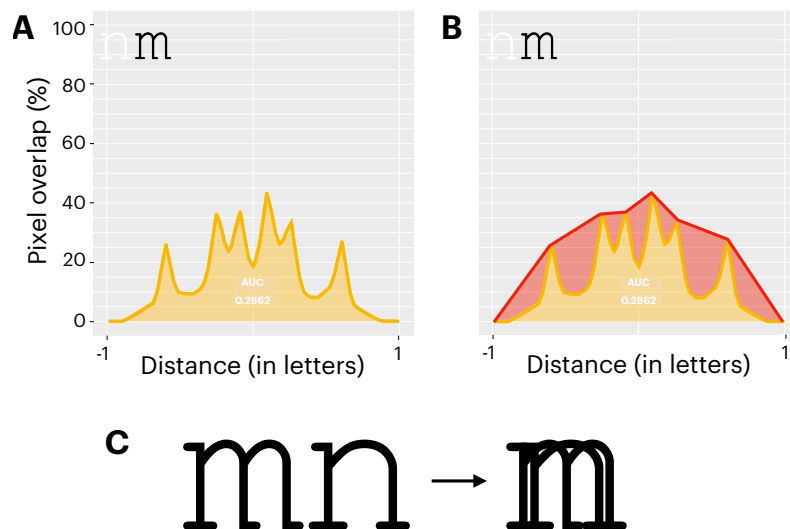


Figure 5.7 (A) For the letter pair n–m (Courier New), the raw moving-window pixel-overlap profile shows several local maxima; a peak-based AUC therefore yields only a modest similarity score, underestimating their obvious visual similarity. (B) A “between-peaks AUC” computed from a smoothed envelope that interpolates across local maxima increases the similarity estimate by integrating the regions between peaks, better matching perceived confusability under degraded input. (C) Rationale for the envelope: the vertical strokes of m and n coincide only at specific window alignments (producing sharp peaks), yet near-miss alignments—where the strokes are close but not perfectly superposed—are still highly confusable; the smoothed envelope would capture these near-alignments instead of discarding them.

In addition, extending the method to variable-width fonts (unlike the fixed-width Courier New) may improve ecological validity, as these fonts better approximate real reading conditions. Another possible refinement would be to consider cross-unit confusability, by estimating whether a word contains (1) a letter that is highly confusable with a bigram, and/or (2) a bigram that is highly confusable with a single letter. Such interactions are common under degraded vision – for instance, the letter m may be perceived as the bigram rn, or the cluster cl as the letter d – and could account for visually confusable words such as clown and down. Capturing these multi-level ambiguities would provide a more integrated account of how local letter shapes interact to produce visual uncertainty, potentially impacting reading performances.

Overall, these findings support the validity of WAM_letter as a robust index of the visual ambiguity inherent to words and confirm that this factor has a measurable impact on reading with simulated central field loss. While several methodological refinements have been identified, these remain to be implemented and experimentally tested in future work. For the purposes of the present dissertation, WAM_letter will therefore serve as the operational measure of visual ambiguity in the following analyses (Chapter 6 and Chapter 7), allowing us to examine how perceptual uncertainty interacts with linguistic and contextual factors in shaping reading performance.

4 Visual ambiguity 20 (VA20)

While WAM quantified intrinsic visual ambiguity within individual words, it did not account for how a word’s form compares to others in the lexicon. In natural reading, visual competition between similar-looking words can influence recognition and lexical access speed (Grainger & Jacobs, 1996). To capture a neighborhood-level component of visual ambiguity, we developed a complementary metric: Visual Ambiguity 20 (VA20).

Commonly used psycholinguistic metrics that have been investigated in previous chapters, such as word frequency, orthographic similarity, or lexical predictability, capture valuable aspects of a word’s properties, but they do not directly quantify the visual resemblance of letter shapes in a given font. For instance, Coltheart’s N defines orthographic similarity as the number of words that can be obtained by substituting a single letter in the target, whereas OLD20 extends this notion by computing the mean Levenshtein distance between a word and its 20 closest neighbors – that is, the minimal number of letter substitutions, additions, or deletions required to transform one word into another. In both cases, however, all possible computations are treated as equivalent, regardless of the physical similarity between the letters involved (e.g. an l-i substitution is equivalent to an l-w substitution).

Figure 5.8 illustrates this limitation using the word *down* and several orthographically close words – *gown*, *town*, *drown*, *clown* and *bowl*. Although *drown* is not a strict N-neighbor (it requires an insertion), it is arguably more visually confusable than *gown* or *town*, which are strict N-neighbors. Furthermore, under the OLD20 metric, the words *clown* (1 insertion + 1 substitution) and *bowl* (2 substitutions) receive an identical edit distance of 2, even though *down* appears to be more visually similar in appearance to *clown* than to *bowl*.

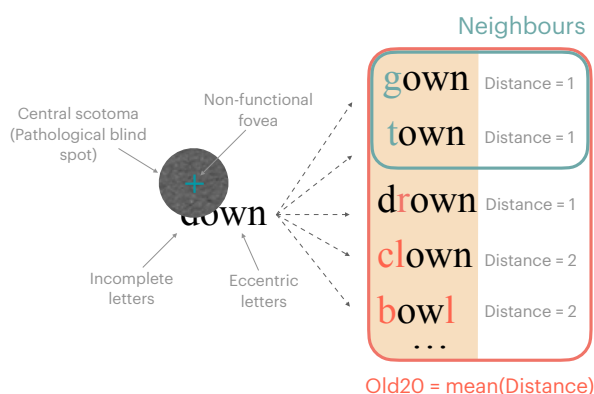


Figure 5.8 Example of orthographic neighbors used by different similarity metrics. The target word is “down”. The distance corresponds to the amount of computations (substitution, addition, deletion) needed to go from the target word to a neighbor.

From these observations, we hypothesize that weighting neighbors by physical letter resemblance could provide a more visually grounded measure of orthographic similarity, especially relevant in populations with visual impairment.

4.1 Definition of VA20

To account for this potential competition, we developed the Visual Ambiguity 20 (VA20) metric — a neighborhood-based measure inspired by OLD20 (Yarkoni et al., 2008) but

grounded in our visual confusability framework. For each target word, we first extracted its 20 closest orthographic neighbors, used to compute the value of OLD20. We then applied our sliding-window pixel-overlap method between the target words and each of their 20 closest neighbors. The VA20 value was then computed as the median of these 20 overlap scores.

High VA20 values indicate that a word’s nearest visual neighbors are highly similar in shape, potentially increasing perceptual competition and misidentification risk under degraded viewing conditions. Conversely, low VA20 values indicate a sparser and visually distinct neighborhood, with few strongly confusable neighbors. We believe that this measure is an even broader measure of orthographic similarity / visual ambiguity, compared to OLD20 and N. In the next section, we compared the effect of VA20, OLD20 and N on reading time.

4.2 Experimental validation of VA20

4.2.1 Effect of VA20 on reading time

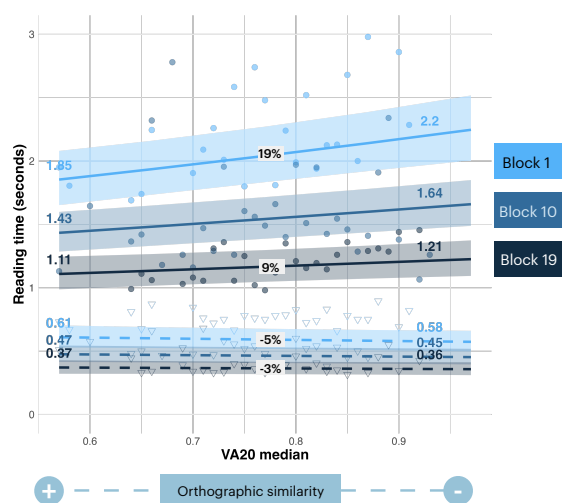


Figure 5.9 Relationship between word reading time and VA20 for the scotoma (solid lines) and control groups (dashed lines) across representative blocks. Lines show model-predicted slopes with 95% confidence intervals.

VA20 significantly predicted reading time under simulated CVL. In the scotoma group, words with higher VA20 values – those most visually similar to their neighbors – were read about 19% more slowly than words with low VA20, indicating that greater visual ambiguity slows reading under eccentric viewing (Figure 5.9). This effect decreased with training, dropping to roughly 10% by the final blocks, suggesting that practice mitigates the influence of visually similar neighbors. In the control group, the effect was minimal ($\approx 5\%$), consistent with the idea that visual ambiguity primarily affects reading when foveal input is unavailable. Overall, VA20

produced effects similar in magnitude to those observed for neighborhood size (N) and OLD20 (see Chapter 4).

4.2.2 Comparison with N and OLD20

To evaluate the contribution of VA20 relative to classical orthographic similarity measures, we first compared three mixed-effects models including respectively N, OLD20, and VA20 as predictors of reading time (see models 1A and 1B from Chapter 4). Model comparison via AIC revealed that, although VA20 captured meaningful orthographic similarity effects, OLD20 remained the best-fitting predictor overall. When directly comparing the linear mixed-effect

results from the present model with models 1A and 1B from (respectively having N and OLD20 as fixed effects), the model including OLD20 has the smallest AIC, meaning that OLD20 is still the predictor allowing for the best fitted model.

To confirm that OLD20 is the most explanatory measure of orthographic similarity, we then created a single model with all 3 predictors to compare them directly and check how the variance of this full model was distributed between them (Table 5.4).

Predictors	Estimates	CI	p
(Intercept)	0.97	0.83 – 1.11	<0.001
logfreq	-0.05	-0.05 – -0.04	<0.001
nbcarr mot	0.01	-0.00 – 0.02	0.060
OLD20	-0.10	-0.15 – -0.05	<0.001
N	0.00	-0.01 – 0.01	0.842
VA20	0.10	-0.15 – 0.36	0.416
block	-0.04	-0.05 – -0.03	<0.001
controls	-1.51	-1.70 – -1.33	<0.001
pred	-0.43	-0.47 – -0.40	<0.001
OLD20 × block	0.01	0.00 – 0.01	0.001
OLD20 × controls	0.15	0.09 – 0.20	<0.001
N × block	0.00	-0.00 – 0.00	0.257
N × controls	0.01	-0.00 – 0.01	0.083
VA20 × block	0.00	-0.02 – 0.02	0.930
VA20 × controls	-0.25	-0.54 – 0.04	0.094
block × controls	0.02	0.01 – 0.03	<0.001
logfreq × controls	0.04	0.03 – 0.04	<0.001
nbcarr mot × controls	0.01	-0.00 – 0.02	0.139
controls × pred	0.30	0.26 – 0.34	<0.001
OLD20 × block × controls	-0.01	-0.02 – -0.01	<0.001
N × block × controls	-0.00	-0.00 – -0.00	0.023
VA20 × block × controls	-0.00	-0.03 – 0.02	0.739

Table 5.4 Fixed effect estimates from a full model including N, OLD20 and VA20 as predictors. Predictors and interactions in bold are significant ($p < 0.05$).

While VA20 added some explanatory power in this combined model, OLD20 remained the strongest predictor of reading time. Model comparisons (through ANOVA likelihood ratio test) confirmed that a model including all three predictors fit better than VA20 or N alone, but did not outperform a model with OLD20 alone, emphasizing the superior predictive value of OLD20 under simulated central vision loss (Table 5.5).

Overall, these results indicate that VA20 captures meaningful visual competition effects in isolation, particularly in the scotoma group, but its contribution is secondary when OLD20 is included (Table 5.5). Thus, while visual ambiguity influences reading under degraded vision, orthographic similarity as measured by OLD20 remains optimal.

Model predictors	Number of parameters	AIC	p-value of LR test
VA20	20	29629	
All three	26	29617	***

Model predictors	Number of parameters	AIC	p-value of LR test
N	20	29661	
All three	26	29617	***

Model predictors	Number of parameters	AIC	p-value of LR test
OLD20	20	29612	
All three	26	29617	ns

Table 5.5. Anova likelihood (LR) ratio test between a model with one versus all three orthographic similarity measures. All models also include other predictors: log-frequency, predictability, length and block number. Models in bold are the better fit.

4.3 Conclusions

Although preliminary results suggest that the effect of VA20 is weaker than OLD20's effect, the measure offers a complementary way to quantify visual similarity between words. By weighting orthographic similarity according to the physical resemblance of letter shapes, VA20 captures a dimension of lexical competition that traditional metrics overlook. These results therefore lay the groundwork for future refinements and extensions of the method.

In particular, subsequent iterations of VA20 could explore weighting neighbors by their frequency, giving greater importance to visually similar words that are more common in the lexicon and therefore more likely to compete during word recognition. The number of neighbors considered in the VA20 metrics could also be adjusted to better reflect lexical density (i.e. VA5 or VA10). Additional developments may also test the method in proportional fonts, which could drastically change our results.

Overall, VA20 represents an important methodological step toward bridging the gap between typographic and psycholinguistic approaches to word recognition. While still exploratory, it opens promising avenues for quantifying how visual and linguistic constraints jointly shape reading under degraded or eccentric vision. At this stage of development, and based on the experimental validation of the measure, we choose to use OLD20 in the upcoming analyses (Chapter 6 and Chapter 7).

Chapter 6 FROM SIMULATION TO PATHOLOGY: READING ADAPTATION ACROSS THE VISUAL AND AGE SPECTRUM

In Chapters 3 to 5, we showed that both psycholinguistic and visual factors significantly influence reading time in young adults with a simulated central scotoma, and that practice reduces the impact of some of these factors.

However, each factor was investigated independently, without trying to rank their relative influence when taken all together. More importantly, these studies focused exclusively on young adults forced to read with eccentric vision because of a gaze-contingent mask displayed around their fixation point. It remains unclear whether the balance between linguistic and visual influences generalizes to a clinical population of older adults with acquired central visual field loss (CVL), or whether age on its own alters the dynamics of adaptation.

The goal of the present chapter was to address these questions. Reading performance from three populations were investigated: patients with CVL (N=48), healthy older adults reading with a simulated scotoma (N=16) and healthy young adults reading with a simulated scotoma (N=22). For each population, we estimated the specific influence of frequency, in-context predictability, orthographic similarity (OLD20), length and visual ambiguity (WAM) on word reading time using mixed-effect models.

Identifying which cues are most strongly exploited in eccentric reading can inform both theoretical models of eye-movement control and practical rehabilitation tools such as text simplification. In addition, understanding how these factors interact under degraded central vision provides insight into how reading processes may change when foveal vision is disrupted.

This work was presented as a talk at the international conference **Vision 2025**.

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1 Introduction

Influence of psycholinguistic factors in normal reading

In normal reading, the contribution of different lexical factors has been extensively characterized (see Chapter 1 for a review). Keith Rayner referred to three of these variables - frequency, length, and predictability in context - as the 'Big three' factors in reading (Rayner, 1998). Word frequency is one of the most robust facilitators: high-frequency words are recognized and read faster, yielding shorter fixation durations (Kuperman et al., 2024; Rayner, 1998). Contextual predictability also exerts a strong influence: words that fit their prior context are processed faster and with a higher skipping rate (Kliegl et al., 2004a; Staub, 2015). Word length reliably affects reading speed, and its influence remains significant even when other lexical variables are controlled for (New et al., 2006). In addition, large cross-linguistic analyses further confirm that word length is a universal determinant of reading performance (Kuperman et al., 2024). Finally, orthographic similarity (often quantified as Coltheart's N or OLD20) also contributes to lexical access, facilitating recognition for words with many close neighbors when vision is intact (Andrews, 1997; Yarkoni et al., 2008). Though, its effects are typically weaker than frequency and predictability, dependent on the neighbors' frequency, and particularly task-dependent (Grainger & Jacobs, 1996; Perea & Rosa Martínez, 2000). Taken together, these findings indicate that several lexical properties jointly shape normal reading. Word frequency, contextual predictability and length exert the most consistent facilitative effects across studies, while orthographic similarity also contributes to lexical access, though its effects are typically weaker and dependent on external factors.

Text simplification

Yet, to our knowledge, no study has ever attempted to rank these factors based on their relative influence on reading performance. Such knowledge could provide a useful baseline for evaluating how the weighting of these cues may shift when central vision is impaired, and reading has to be performed with eccentric vision. Indeed, assessing the relative impact of these factors when reading with CVL would be a crucial keystone in the development of text simplification tools targeted for individuals with low vision. Text simplification is the process of reducing the linguistic complexity of a text, while still retaining its original content and meaning (Scarton, 2020; Siddharthan, 2014). It was originally designed to make a text more accessible to individuals with low literacy (Candido et al., 2009) or suffering from reading disorders such as dyslexia (Rello et al., 2013) or aphasia (Carroll et al., 1999). It has already been extensively and efficiently used in these populations. As demonstrated recently, text simplification might also become a powerful tool to leverage text accessibility for low-vision patients with CVL (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrese, 2020). Yet, features that make a text complex for readers with dyslexia may not be the same for impaired readers with a visual disorder, such as CVL. And text simplification must be tailored to each specific population. Hence, designing text simplification rules for CVL patients requires to gather experimental knowledge about the relative influence of both psycholinguistic and visual text features when reading with CVL, which will be at the core of this chapter.

Influence of psycholinguistic factors with CVL

To date, the influence of psycholinguistic factors when reading with CVL has not been much investigated yet. Still, a handful of studies have shown that CVL patients highly benefit from lexical cues such as frequency and neighborhood size, but also exhibit significant effects of visual factors such as word length (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019). In addition, these cues were not always found to influence reading performance in the same manners as in normally sighted reading – some effects were amplified (Stolowy et al., 2019), others reversed (Sauvan et al., 2020). Indeed, in the presence of a central scotoma, bottom-up visual input becomes less reliable, possibly forcing patients to rely more on top-down linguistic inference than normally sighted readers (Calabrèse, Bernard, et al., 2016). According to this hypothesis, the linguistic properties of a text should exert a stronger influence on performance when reading with CVL compared to normal vision. The present chapter will be devoted to test this hypothesis, by investigating the overall influence of word frequency, contextual predictability, orthographic similarity and length on the reading performance of patients with CVL.

WAM

In addition to the factors cited above, this thesis introduced a new word feature that could influence reading with eccentric vision: the Word visual Ambiguity Measure (WAM). This visual factor represents a complementary metric that captures the visual confusability of letters within a word (see Chapter 5 for details). Previous research has already demonstrated that reading under degraded visual conditions can be slowed down by the perceptual similarity of printed characters. Hence, visual confusability constitutes a limiting factor for letter and word recognition (Bouma, 1971; Pelli et al., 2006), whose impact increases in peripheral vision because of crowding (Levi, 2008; Pelli & Tillman, 2008). Based on these findings, we hypothesize that, when reading with eccentric vision, the visual ambiguity yield by the presence of letters that share similar features, may have a strong impact on word identification, and in turn slow down reading speed. In this chapter, we will integrate WAM to the analysis of the word features that influence reading with eccentric vision. We aim to isolate the specific influence of word visual ambiguity on reading performance. According to our hypothesis, we expect to find a larger influence of WAM when reading with eccentric vision (either with a simulated or a pathological scotoma), compared to reading with central vision.

2 Methods

2.1 Participants and paradigm

Three populations were included in this study: patients with CVL, healthy older adults and healthy young adults. All read sentences using the self-paced reading paradigm. Healthy individuals (both young and older) either read with a simulated scotoma or performed the task without a simulated scotoma using their central vision. General methodology is described in detail in Chapter 2 and summarized in Table 6.1.

		Self-Paced reading paradigm	Sentence corpus	Experimental setup	Outcome measures
Older adults with central visual field loss					
Patients enrolled during this thesis		N = 10 (3F / 7M) Mean age = 78.7 ± 6.6	Corpus #1 (subset) 64 sentences	Virtual reality	Accuracy Reading time
Data from previously recruited patients		N = 38 (29F / 9M) Mean age = 75.6 ± 11.4	Corpus #2 80 sentences	Computer screen	
Healthy older adults					
Visual condition	Control	N = 8 (6F / 2M) Mean age = 68.9 ± 4.3	Corpus #1 304 sentences	Computer screen + eye tracker	Accuracy Reading time
	Simulated scotoma	N = 16 (11F / 5M) Mean age = 68.9 ± 4.1			
Healthy young adults					
Visual condition	Control	N = 13 (6F / 7M) Mean age = 24.3 ± 1.8	Corpus #1 304 sentences	Computer screen + eye tracker	Accuracy Reading time
	Simulated scotoma	N = 22 (15F / 7M) Mean age = 22.7 (2.4)			

Table 6.1. Summary of experimental groups and conditions included in this study, as well as the corpus, experimental setup and outcome measures. In the simulated scotoma groups, 9 participants (5 young; 4 older) who did not reach a learning plateau (see Chapter 2 Section 6.1.2 for details) were not included in this study.

2.2 Data processing

For each word read, we recorded its accuracy and reading time. Misread words were coded as inaccurate (accuracy = 0). Reading time was estimated in seconds as the time each word was displayed on the screen. Misread words were excluded from analyses of reading time.

The whole analysis was performed by splitting our group of patients according to their daily reading time, taking into account their reading habits. Hence, patients were split within two distinct subgroups: patients who still practice reading on a daily basis, even a few minutes each day, versus patients who reported having stopped reading at all. This distinction should allow for comparisons with previous literature and was decided upon based on the results from (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a), who reported different reading patterns depending on the patients' reading habits.

As described in Chapter 2, all patients were tested on the MP-3 microperimeter to estimate the characteristics of their scotoma and fixation pattern. Because of experimental constraints, we only got access to the MP-3 data collected in 10 patients from the 48 included in this analysis. Data extracted from this examination were first included in our analysis. But the small amount of data did not allow to draw any statistically relevant conclusions. Therefore, we decided not to use MP3 data in the present analysis.

For the simulated scotoma groups, we wanted to ensure that the analysis was performed using data collected once participants were trained to the presence of the scotoma. This step was crucial to make performance in simulated participants more comparable to that of pathological readers, as simulated readers need several blocks to adapt to the central field

mask forcing them to use eccentric vision. As described in detail in Chapter 2 Section 6.1.2, a learning curve was estimated for each healthy participant reading with a simulated scotoma. Average reading time was plotted as a function of block number. For each plot, we estimated the breakpoint(s) and derived a plateau of performance. All blocks included in this plateau showed stable reading time with reduced variability, leading us to consider the individual as “trained”. Only data from blocks within the plateau were included in the present analysis.

2.3 Statistical Analysis

Influence of word characteristics on word Reading Time (RT) was analyzed using linear mixed-effects models in R. Only words identified accurately were included in this analysis. Separate models were estimated for each population of interest:

- Model 1. Patients with CVL, grouped depending on their reading habits (daily readers vs. individuals who have stopped reading)
- Model 2. Healthy older adults reading with a simulated scotoma
- Model 3. Healthy young adults reading with a simulated scotoma

In each model, RT was log-transformed and used as the dependent variable. Fixed effects were the same in all three models: log word frequency, in-context word predictability, OLD20, length and Word visual Ambiguity Measure (WAM; cf. Chapter 5 for details). Each of these continuous predictors was z-standardized (mean 0, SD 1). Standardization sets predictors on a comparable scale, which facilitates model convergence and allows direct comparison of regression coefficients across predictors. In Model 1, an additional fixed effect was included: the categorical factor “Reading habit” which classified patients as *Daily readers* (patients who still practice reading on a daily basis, even a few minutes per day) or *Quit reading* (for those who have quit reading, and reported reading 0 minutes per day). The interaction between Reading habit and each of the predictors listed above was also included. Random structure was the same for all three models, with random intercepts for subjects and items (defined as unique word–sentence combinations), plus a random intercept for grammatical category.

3 Results

3.1 Participants

Table 6.2 shows demographic information for the 95 participants included in this analysis, broken down according to their visual status and age: patients with CVL, healthy older adults and healthy young adults. It is worth noting that 44 % of our pathological population reported having quit reading on a daily basis because it became simply too difficult to perform this task (even though patients were not recruited to balance out the *Quit reading* vs. *Daily readers* groups).

		N	Gender (F / M)	Age (years)	Decimal visual acuity	Years since diagnosis	Daily reading (min)
Patients	Quit reading	21	17 / 4	76 ± 8	0.15 ± 0.08	12 ± 15	0 ± 0
	Daily readers	27	15 / 12	76 ± 13	0.15 ± 0.10	13 ± 9	51 ± 67
Healthy older adults		20	14 / 6	69 ± 4	1.00 ± 0.00	--	92 ± 59
Healthy young adults		27	17 / 10	23 ± 3	1.00 ± 0.00	--	341 ± 217

Table 6.2. Demographic and clinical characteristics of patients with CVL included in this study. The table reports the number of participants (N), gender distribution, age, visual acuity, years since diagnosis and self-reported daily reading time. Those values are expressed as mean ± standard deviation.

3.2 Descriptive statistics of the patients’ reading performance

Reading accuracy did not differ between groups (Figure 6.1 - left), with an average percentage accuracy of $95.9 \pm 6.9\%$ for the patients who have stopped reading on a daily basis and $97.6 \pm 1.9\%$ for the ones who maintain some daily reading practice, even a few minutes per day. However, reading time (Figure 6.1 - right) was longer in the group of patients who stopped reading daily (4.7 ± 2.4 seconds) compared to the patients who still read on a daily basis (3.3 ± 1.1 seconds). These results suggest that despite their longer reading time, patients who have stopped reading daily make little to no mistakes, at the cost of their reading speed. In the remaining of this analysis, only words read correctly will be included.

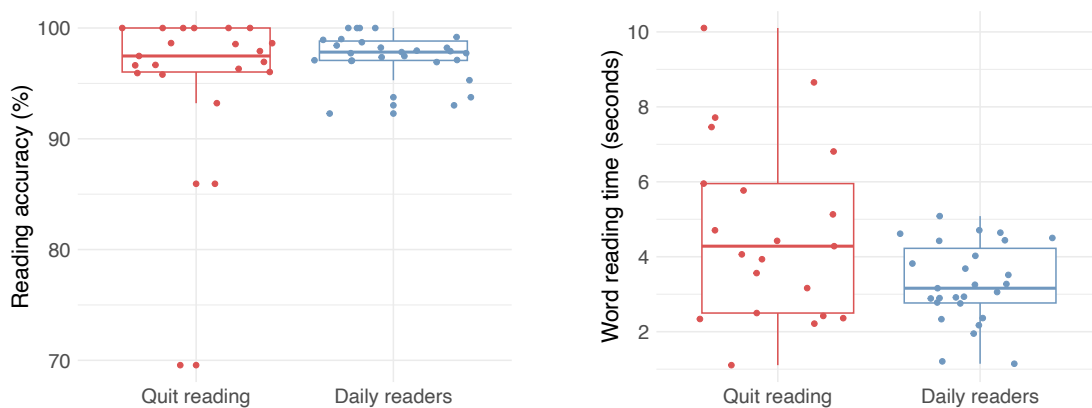


Figure 6.1. Reading performance of the 48 patients, grouped according to their reading habits: patients who quit reading (in red) and daily readers (in blue). The left panel shows the percentage of well-read words; the right panel shows the average word reading time. Each data point represents a single patient.

3.3 Influence of each word feature on word reading time

Results from patients (Model 1) are reported in Table 6.3 and presented in Figure 6.2. Results from adults reading with a simulated scotoma (Models 2 and 3) are also provided for comparisons. Overall, reading time was longer for patients who have quit reading daily (in red in Figure 6.2), followed by patients who still read daily (in blue in Figure 6.2), then by older adults reading with a simulated scotoma (in dark green in Figure 6.2). Young adults reading

with a simulated scotoma (in light green in Figure 6.2) exhibited the shorter reading time. Below we describe the output of these models, which estimate the effect on word reading time of each word feature investigated, while accounting for the influence of all other factors.

Frequency

For patients who still read daily, reading time decreased significantly when frequency increases ($t = -15.54$). For patients who have quit reading, the same effect persists, but with a slightly smaller amplitude ($t = 2.03$). Same thing for older adults, for whom the amplitude was even smaller, while still being significant ($t = -10.55$). Similarly, the effect was significant for young adults with a slightly smaller amplitude ($t = 12.36$). Overall, the positive effect of frequency was consistent across populations (the more frequent a word is, the quicker it is read) but its amplitude decreased slightly in each population.

In-context predictability

When predictability increases, reading time decreases significantly in both groups of patients ($t = -6.01$). There is no significant interaction between predictability and reading habits ($t = 1.69$), meaning that the facilitating effect of this predictor has the same amplitude in both groups. In older adults the effect is also significant and has the exact same amplitude ($t = -5.92$), whereas it is significant with a slightly smaller amplitude in young readers ($t = -6.50$).

Orthographic similarity (OLD20)

Daily readers showed a small but significant facilitating effect of OLD20 ($t = -2.46$). In the quit reading group, the effect was significantly different from the daily readers ($t = 2.03$) with a null amplitude. Similarly, healthy readers experienced no significant influence of OLD20 on their reading time ($t = -1.58$ for older adults and $t = -1.26$ for young adults).

Word length

Reading times increased significantly with word length in patients who still read daily ($t = 5.88$), indicating that longer words required more time to read. This effect persisted in the quit reading group with a significantly larger amplitude ($t = 2.22$). Healthy adults also experienced a significant effect of length of the same amplitude regardless of their age group ($t = 2.40$ for older adults and $t = 2.72$ for young adults), but the amplitude of the effect was of smaller amplitude compared to the patients.

Visual ambiguity (WAM)

In all four groups, higher visual ambiguity was associated with significantly longer reading time ($t = 2.42$ in patients, $t = 6.35$ for older adults and $t = 5.22$ for young adults). The effect appeared to be slightly weaker in daily readers compared to the quit reading group, but this difference was not significant ($t = 1.66$).

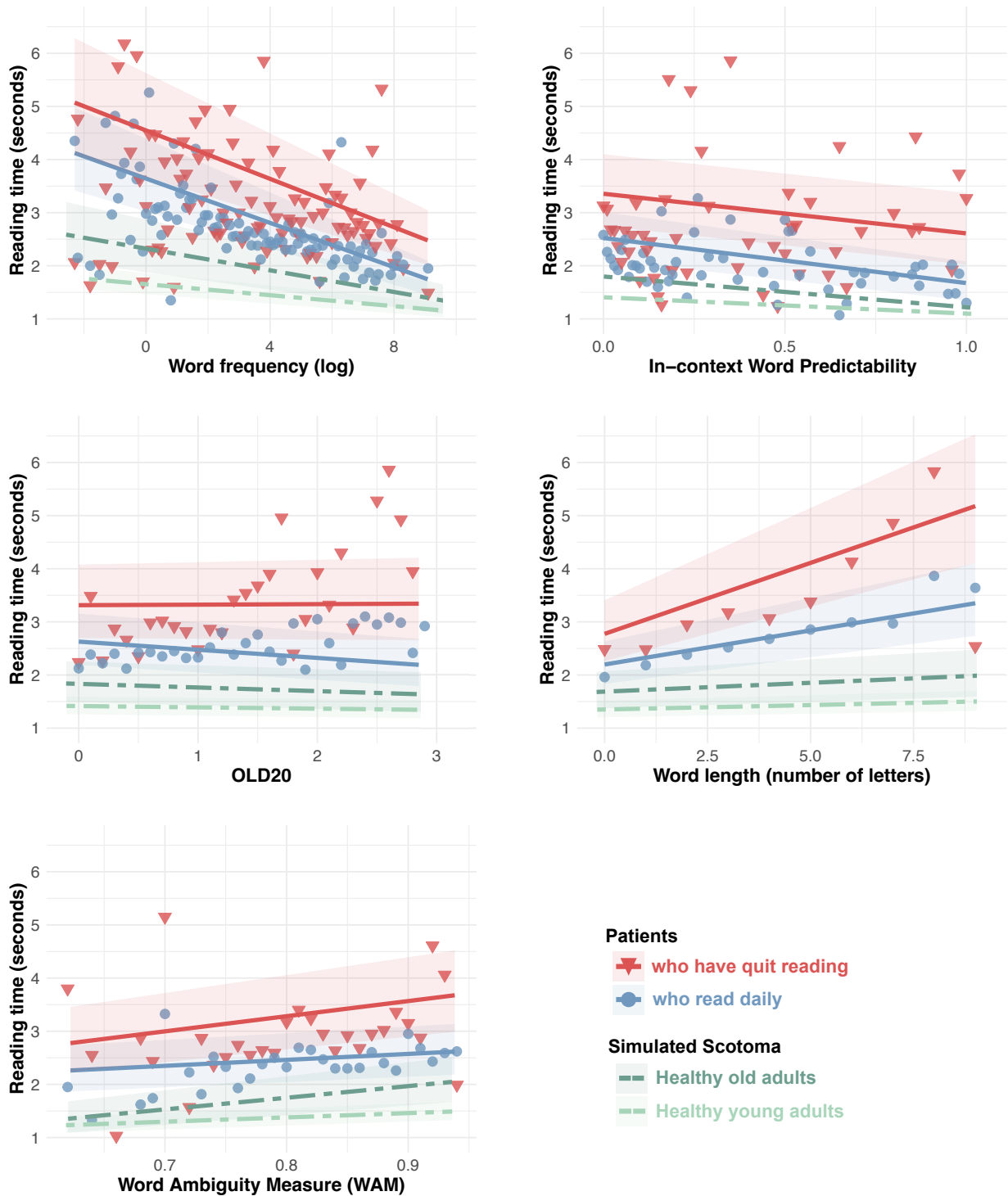


Figure 6.2. Fitted effect of psycholinguistic and visual word features on word reading time as estimated by Model 1 (patients with CVL), Model 2 (healthy older adults) and Model 3 (healthy young adults). Each panel shows a different factor: frequency, in-context predictability (top row), OLD20, length (middle row) and Word visual Ambiguity Measure (WAM; bottom row). Raw data are only provided for patients who have quit reading (red triangles) and patients who still read daily (blue circles). Straight lines represent the effects as estimated by the models. Shaded areas indicate their 95 % confidence intervals.

Predictors	Model 1 Patients		Model 2 Healthy older adults		Model 3 Healthy young adults	
	Estimate	t-value	Estimate	t-value	Estimate	t-value
(Intercept)	0.91 ***	10.14	0.57 ***	5.62	0.33 ***	5.75
Frequency	-0.17 ***	-15.54	-0.12 ***	-10.55	-0.08 ***	-12.36
Predictability	-0.05 ***	-6.01	-0.05 ***	-5.92	-0.03 ***	-6.50
OLD20	-0.04 *	-2.46	-0.02	-1.58	-0.01	-1.26
Length	0.09 ***	5.88	0.03 *	2.40	0.02 **	2.72
Visual ambiguity (WAM)	0.02 *	2.42	0.06 ***	6.35	0.03 ***	5.22
Quit reading	0.29 *	2.20	--	--	--	--
Quit reading:Frequency	0.03 *	2.03	--	--	--	--
Quit reading:Predictability	0.02	1.69	--	--	--	--
Quit reading:OLD20	0.04 *	2.03	--	--	--	--
Quit reading:Length	0.04 *	2.22	--	--	--	--
Quit reading:Visual ambiguity (WAM)	0.02	1.66	--	--	--	--
Observations	6009		5624		10015	
Conditional R ²	0.605		0.445		0.358	

Table 6.3 Fixed-effect estimates from the linear mixed-effects models examining the effect of psycholinguistic and visual word features on word reading time in: (1) patients with CVL (Model 1), (2) healthy older adults (Model 2) and (3) healthy young adults (Model 3). Continuous predictors were z-standardized. Interaction terms (represented by the symbol “:”) capture the modulation of each predictor by the level of reading habit (daily reading vs. quit reading).

3.4 Relative influence of the different factors

In the previous section, we reported the effect amplitude of the five word-features investigated (namely word frequency, in-context predictability, OLD20, length and WAM). These results show that increasing word frequency and predictability significantly reduce reading time in both patient groups, while increasing word length and visual ambiguity increases it. However, daily readers seem to exhibit a reduced sensitivity to both these visual factors (word length and WAM), compared to those who have quit reading. Yet, it is hard to draw such conclusion based on Table 6.3 and Figure 6.2 because these representations do not allow to clearly grasp the relative influence of each factor.

To better address this question, we extrapolated the results from Model 1, 2 and 3 to extract the percentage of reading time difference yield by each factor increase. Results are presented through simple histograms as described below. Each bar illustrates the impact of one factor on reading time, as estimated by the corresponding mixed-effects model. Figure

6.3 illustrates this procedure: reading time was plotted as a function of one factor (e.g., log-transformed frequency) using model predictions. For each factor, we extracted the predicted reading time at its minimum and maximum values. The histogram then represents the percentage change in reading time between these two values, expressed in absolute terms.

For example, in Figure 6.3, predicted reading time decreases from 5.1 seconds at the lowest word frequency to 2.5 seconds at the highest frequency, corresponding to a 51% modulation. The associated histogram therefore shows a 51% effect for frequency. This simplified visualization provides an intuitive overview of each factor’s relative influence on reading time, allowing for direct comparison.

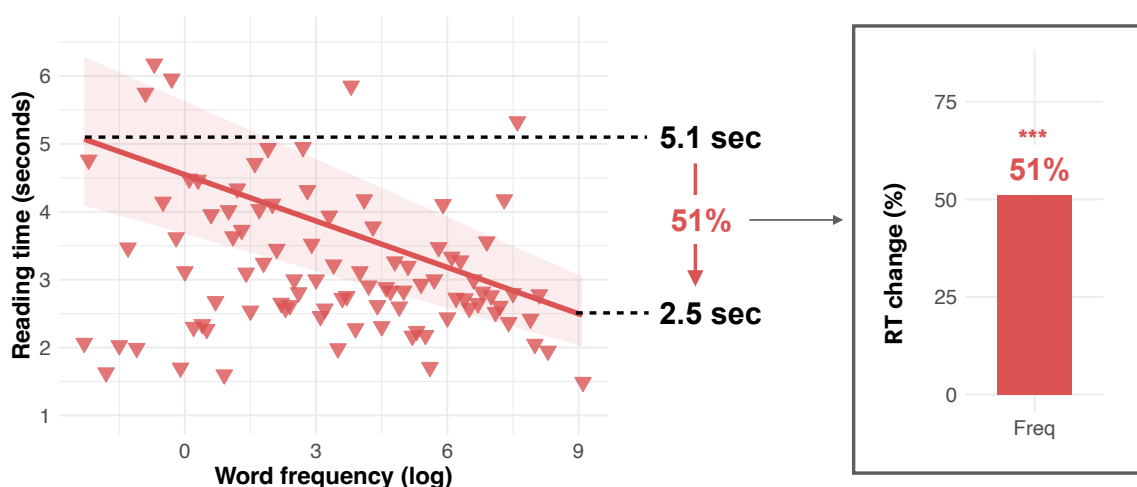


Figure 6.3. Left: Relationship between word reading time and log-transformed word frequency, plotted for all patients. The solid line shows the model-predicted slope with a 95% CI, representing the effect of frequency estimated by Model 1. Right: Simplified representation in the form of a histogram, illustrating the percentage change in reading time associated with frequency.

3.4.1 Patients

Results are presented in Figure 6.4. In both groups of patients, frequency, predictability and OLD20 showed the same relative hierarchy - frequency always has a stronger impact compared to predictability, which in turn, has a strongest impact than OLD20. These three psycholinguistic factors show a tendency of slightly larger amplitude effect for patients who still read daily: 58% against 51% for frequency, 34% against 22% for predictability and 17% against 1% for OLD20. The strongest difference between the two groups seem to take place in the influence of the visual factors, namely word length and WAM, which show a much stronger impact on reading time for patients who have quit reading daily. More importantly, their influence seem to overcome the one of the psycholinguistic factors. This stronger reliance on length and WAM, which both describe visual properties of text, experienced by patients who do not practice reading anymore, suggests that the reading performance in this group were more strongly impacted by visual cues.

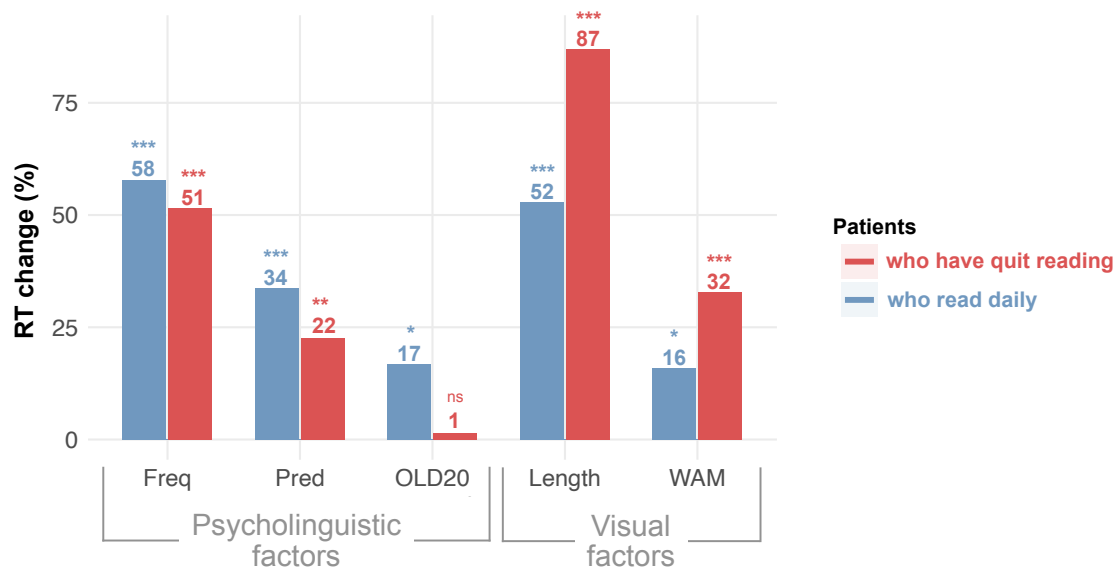


Figure 6.4 Relative influence of word features in patients who read daily (blue) and patients who have quit reading (red).

3.4.2 Healthy adults

Results for age-matched healthy individuals reading with a simulated scotoma (Figure 6.5 - green) show that the influence of the three psycholinguistic factors (frequency, predictability and OLD20) is consistent with what was found for patients who still read on a daily basis (Figure 6.4 - blue). The frequency effect shows an amplitude of 50% (against 58% for patients), the predictability effect shows an amplitude of 41% (34% for patients) and the influence of OLD20 shows an amplitude of 12% (17% for patients). Overall, the ranking of psycholinguistic influences remains the same as in patients, even though the magnitude of these effects was slightly smaller. Visual factors however do exhibit different patterns compared to patients, with a very large influence of WAM (51%), while length shows a significant but moderate influence (19% only). In other words, when WAM goes from its smaller value (limited visual ambiguity within a word) to its larger possible value (higher visual ambiguity), reading time increases by 51%. As a reference, Figure 6.5 also presents results for the group of healthy older individuals who read without a simulated scotoma, using their central vision, as normal. One can see that all psycholinguistic factors show larger amplitude with eccentric vision, which goes along with the hypothesis of an increased reliance on linguistic inference in readers with central visual field loss.

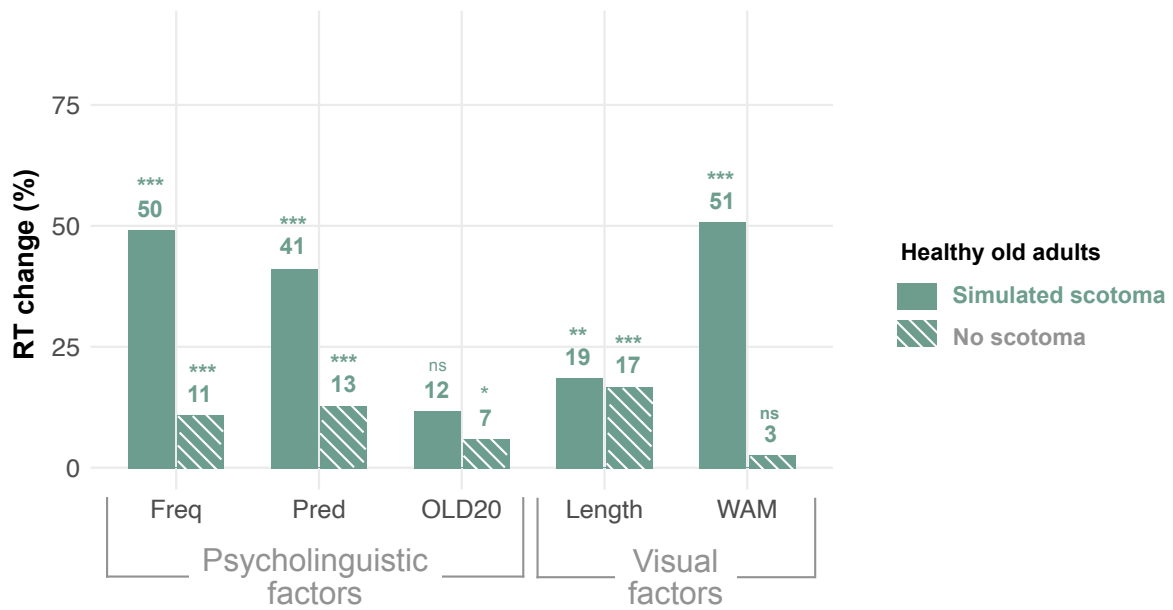


Figure 6.5 Older adults reading with a simulated scotoma versus older adults reading with central vision.

Profiles were similar between older and young healthy adults forced to read with eccentric vision (Figure 6.7), although all factors showed a smaller influence on reading time for the younger group. Again, frequency remained the strongest predictor, followed by predictability, OLD20, and length. WAM however did show a much reduced amplitude in the young group. However, in both groups, WAM exerted a strong impact, compared to what had earlier been described in patients.

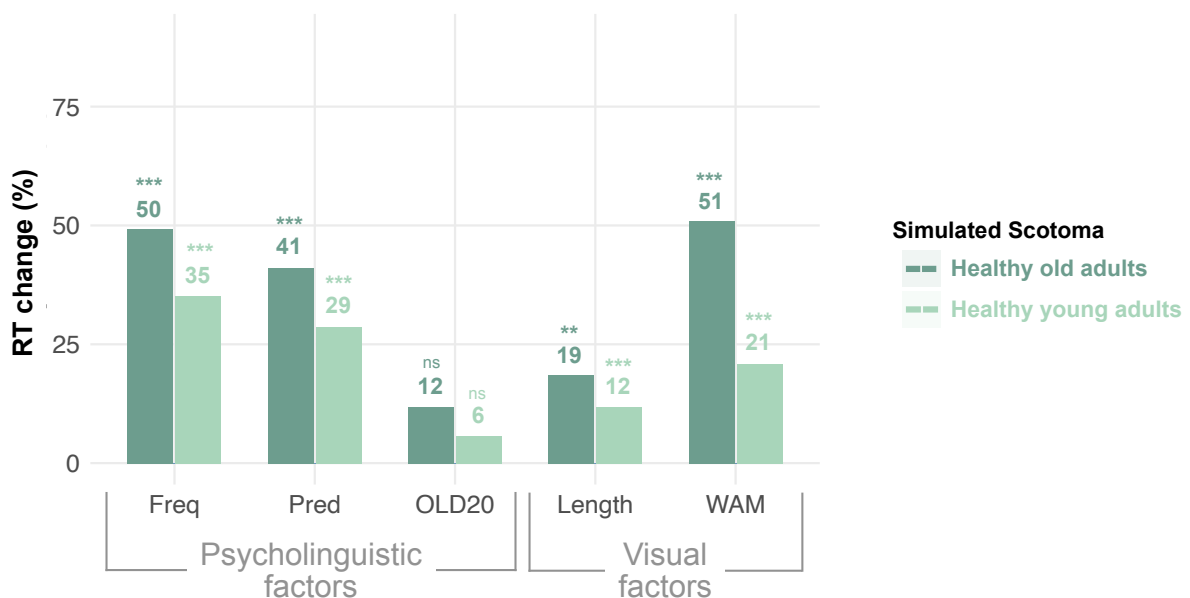


Figure 6.6 Older adults reading with a simulated scotoma versus younger adults reading with a simulated scotoma.

As illustrated in Figure 6.7, profiles were also similar between older and young healthy adults reading without a simulated scotoma, hence using their central vision as usual. These results

are especially relevant in the context of the study of reading with aging, showing that despite a tendency for slower reading speed, older adults tend to use psycholinguistic and visual cues in a same manner as their younger counterparts.

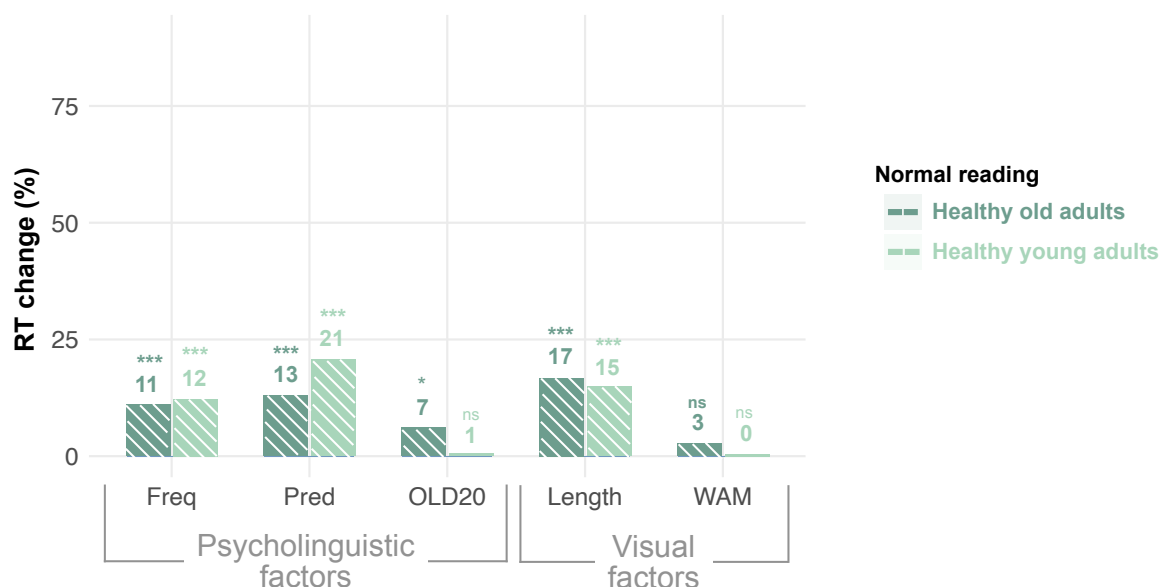


Figure 6.7 Young adults reading with a simulated scotoma versus young adults reading with central vision.

4 Discussion

In this chapter, we aimed to gather experimental knowledge about the relative influence of both psycholinguistic and visual text features when reading with CVL, with a special emphasis on their interaction with individual daily reading habits.

Reading habits

Overall, reading times were shorter in daily readers than in those who had quit reading, confirming a global benefit of sustained reading practice. Prior studies have already identified substantial variability across patients, largely depending on their daily reading habits - individuals who continue to read regularly tend to maintain faster reading speeds (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). Strong reading habits have also been positively associated with better comprehension in normally sighted older adults, suggesting a potential protective role of lifelong reading habits (Riffo et al., 2025). Yet, it is striking that almost half of our pathological population (44 %) reported having quit reading on a daily basis (because the task became too difficult), even though patients were not recruited to balance out the *Quit reading* vs. *Daily readers* group. Together, these results indicate that sustained reading practice may foster adaptive mechanisms that support reading performance under CVL, strengthening the need to develop efficient methods to maintain daily reading in patients with CVL.

Text simplification

Text simplification used as reading aid could be an efficient way to ease reading for patients, especially those who have stopped reading altogether. By making text more accessible, text simplification would help them regain some daily reading practice, in turn fostering overall performance improvement. The results presented in this chapter constitute a milestone for the design of such tool.

First, we found that the hierarchy of psycholinguistic predictors is conserved across all groups of participants reading with eccentric vision: frequency exerted the strongest effect, followed by predictability, and, to a much lesser extent, orthographic similarity (OLD20). This pattern is consistent with prior evidence from both normal (Andrews, 1997; Grainger & Jacobs, 1996; Rayner, 1998) and eccentric reading (Lapeyre et al., 2025; Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a; Stolowy et al., 2019), and suggests that frequency remains the dominant psycholinguistic cue even under degraded visual input. Beyond describing group differences, this result also informs theoretical models of eye-movement control. Both E-Z Reader (Reichle et al., 2003) and SWIFT (Engbert et al., 2005) assign a central role to lexical frequency in driving fixation durations. Our finding that frequency remains the strongest predictor, even under eccentric viewing, directly supports this assumption and extends its validity to conditions of CVL. It also provides guidance for rehabilitation strategies: text simplification interventions specifically adapted to patients with CVL should prioritize high-frequency, highly predictable words, as these cues are most robustly exploited across populations and allow for the most reduced reading time.

Second, we reported that the impact of word length varied systematically with daily reading habits. Patients who had quit reading no longer maintained automatized lexical processing; as a result, they relied more heavily on length, while linguistic cues were used less efficiently (Figure 6.4). In contrast, patients who read daily seemed to treat length only as a secondary cue, and in simulated participants its influence was reduced even further (Figure 6.5 and Figure 6.7). This pattern is consistent with Grainger and Ziegler's psycholinguistic dual route model of orthographic processing (2011), which posits a fast, coarse-grained route relying on the most visible letters to activate word identities rapidly. Under degraded visual input, this information becomes less reliable, plausibly reducing the efficiency of the coarse route and shifting reliance on the slower, fine-grained, letter-by-letter mechanism. Both daily and quit readers therefore depend primarily on this fine-grained route, but daily readers appear to use it more efficiently, likely because regular reading practice preserves the automatization of lexical access and the ability to integrate top-down contextual cues. In contrast, quit readers may process each word more serially, with weaker lexical feedback, leading to slower and more effortful reading. Taken together, these findings highlight the idea that regular reading practice protects lexical efficiency and prevents a drift toward slow, visually driven processing.

In practical terms, these results could be used to set specific rules for text simplification. For instance, for the less proficient readers who do not read daily, substituting complex words (i.e., long words with low-frequency) with synonyms that are shorter with a higher frequency

should reduce reading difficulty. On the other hand, for readers who still practice reading daily, only frequency should be taken into account when choosing the best candidate for synonym substitution. Overall, using simplified texts with increased accessibility as rehabilitation training material could help (1) improve overall reading ability and fluency, while (2) fostering the long-term motivation necessary to resume daily reading practice. Text simplification could then be used daily as an efficient reading aid (made available through tablets, e-readers, or web plugins) to keep practicing reading at home and enhance everyday reading performance.

OLD20

Our results show that OLD20 does not exert a strong influence on reading time in patients (who have lived with a pathological scotoma for years), which is consistent with the results reported in Chapter 4, showing that the effect of OLD20 disappeared once participants got used to reading with a simulated scotoma.

Yet, the effect of orthographic similarity reported in the present study differ significantly from the ones reported previously in a population of CVL readers (Sauvan, Stolowy, Aguilar, François, Gala, Matonti, Castet, & Calabrèse, 2020a). This discrepancy may be due to the different methodological choices we made in the present work, to try and improve overall methods. First of all, despite the fact that both datasets come from the same experiment, they are quite different in many aspects. First, we analysed almost all words from a sentence, including several grammatical classes, while Sauvan et al. (2020) used only specific target words (only nouns). Second, we measured predictability in a different manner (the present being more representative of the written language). Orthographic similarity was also estimated differently, using OLD20 in the present work, while Sauvan et al. (2020) used N (the number of strict orthographic neighbors). As reported in Chapter 4, OLD20 constitutes a better measure of orthographic similarity.

Despite these methodological differences, we wanted to understand why our results on the effect of orthographic similarity differed from the ones from Sauvan et al. (2020). To allow for a direct comparison with their results, the analysis performed in this chapter was reproduced to match theirs (using N instead of OLD20 and adding an interaction between N and predictability). Yet, we were not able to reproduce results from Sauvan et al. (2020), the effect of N being null, suggesting that orthographic similarity does not significantly influence reading performance with eccentric vision. Given that OLD20 and length are strongly correlated (Yarkoni et al., 2008), which was confirmed in the present dataset ($R^2 = 0.74$, $95\%CI = [0.73, 0.75]$), we tried to fit the model presented in this chapter while removing length as a fixed effect. We found that when length is not taken into consideration, OLD20 becomes strongly and significantly influential of reading time. We conclude that the effect of orthographic similarity found in Sauvan et al. (2020) may be due to an under-expressed effect of length in their dataset. In other words, it is likely that the range of word length was not representative enough in Sauvan et al. (2020), not allowing the factor to show its full effect, and in turn leaving room for orthographic similarity effect to express.

WAM

The present analysis allowed us to test our newly developed measure of visual ambiguity (WAM) in a population of patients with CVL, not only healthy readers forced to read with eccentric vision. We found that WAM significantly affected reading time in both patients and simulated readers. When comparing the effect of WAM in the simulated condition versus central vision reading, for both young and older participants (Figure 6.5, Figure 6.7 and Figure 6.7), its effect was exacerbated, confirming our hypothesis that visual ambiguity between letters within a word do influence reading time strongly in eccentric vision, and that WAM allows to capture this effect.

Age effect

Young healthy individuals forced to read with eccentric vision were overall faster than older readers (mean RT \approx 1.55 s vs. 2.27 s), consistent with age-related slowing in lexical access and eye movements. Even in central vision, older adults read more slowly, with longer fixations and more regressions, and show increased sensitivity to visual crowding (Liu et al., 2017; Warrington et al., 2018). Nevertheless, text comprehension accuracy is largely preserved until late adulthood (Akutsu et al., 1991), suggesting that higher-level linguistic processing can compensate for visual and oculomotor constraints. At the lexical level, however, older adults show amplified effects of frequency (Warrington et al., 2018). In addition, older adults rely more on contextual cues during reading, as a compensatory strategy for age-related declines in other cognitive or perceptual abilities (Steen-Baker et al., 2017; Stine-Morrow et al., 2006).

During data collection, older participants often appeared to struggle more with the task: they required additional sessions to complete the experiment and showed greater signs of fatigue. Combined with their slower reading performances, these observations suggested that older adults might not adapt as rapidly as younger readers. This was confirmed by our analyses learning curves analysis (Chapter 2), showing that more blocks were included in the performance plateau and considered as “trained” for young participants. This indicates that both groups follow a comparable adaptation path, but at different speeds, with older readers reaching the same stage later in the experiment. This slower progression is consistent with the processing-speed theory, which attributes age-related cognitive slowing to reduced efficiency in executing and coordinating mental operations (Salthouse, 1996). In our context, slower processing may simply delay the rate at which older readers learn to efficiently process text in eccentric vision.

Beyond cognitive slowing, visual-perceptual changes with aging likely amplify these effects. Older adults experience stronger visual crowding and a smaller visual span compared to younger adults, limiting the number of letters that can be processed in a single fixation (Liu et al., 2017). Such constraints are particularly detrimental under a simulated scotoma, where reading already depends on maximizing the use of eccentric vision – an ability further challenged by increased crowding in eccentric vision (Pelli et al., 2007).

Consistent with these limitations, perceptual learning studies show that while older adults can still improve peripheral reading performance through training, their gains are typically smaller than those of younger adults (D. Yu et al., 2010). Our results align closely with this pattern: older simulated readers adapted more slowly, but their reading performances still show a plateau of performance by the end of the experiment for 15 out of 18 participants, indicating that perceptual plasticity is preserved, even though reduced in magnitude.

Young readers, in contrast, progressed beyond this intermediate stage and developed even more efficient reading patterns in later blocks - marked by stronger reliance on predictability and reduced influence of orthographic similarity. This suggests that aging does not alter the mechanisms of adaptation but limits how far they can be refined within a given amount of practice. In Chapter 7, we will further investigate the influence of age on the development of adaptive strategies, by inspecting eye movement pattern changes in both groups during their adaptation to the scotoma. Further experiments should determine whether extended training could enable older adults with a simulated scotoma to reach the performance levels observed in younger participants after full adaptation.

These findings have clear implications for rehabilitation. They suggest that structured and sustained practice can progressively shift reading in patients with central vision loss toward the more efficient, linguistically driven profiles observed in simulated readers. In this sense, young trained readers represent an upper bound of adaptive potential - showing what eccentric reading can achieve when both exposure and plasticity are maximized. As shown by Chung (2011), perceptual learning can enhance reading speed in individuals with central vision loss even without measurable improvements in acuity or fixation stability (S. T. L. Chung, 2011). Similarly, our results indicate that, although age slows the rate of adaptation, the capacity to develop efficient reading strategies remains intact when sufficient practice and exposure are provided.

5 Conclusion

Together, these experiments demonstrate that reading adaptation under central vision loss depends strongly on both visual constraints and reading practice. Across all groups, frequency and predictability remained the most powerful linguistic cues, confirming their robustness even under degraded visual input. However, the efficiency with which these cues are used varies significantly: patients who continue to read daily and simulated readers rely primarily on linguistic information, whereas those who have stopped reading revert to slower, length-based strategies.

Age further modulates the pace of adaptation rather than its nature: older simulated readers follow the same trajectory as younger ones but progress more slowly. These findings highlight that efficient eccentric reading can be achieved through sustained exposure and practice, and that training may help patients approach the optimized, linguistically driven profiles observed in individuals reading with a simulated scotoma.

From a rehabilitative perspective, these results emphasize the importance of regular reading practice and targeted text simplification. Training programs should encourage sustained engagement with simplified text materials favoring frequent and predictable words - those most robustly exploited under eccentric viewing. At the same time, the differences observed between simulated and clinical readers remind us that simulation can approximate, but not fully reproduce, the challenges of pathological vision loss. A combination of controlled simulation and real-world patient training offers the most promising approach for developing effective, evidence-based reading interventions.

Part IV – Exploring adaptive reading strategies in eccentric reading

Chapter 7 EYE MOVEMENT ADAPTATION AND VISUAL DETERMINANTS OF PRL POSITION DURING READING WITH A SIMULATED SCOTOMA

This chapter examines how readers adapt their eye movement patterns when central vision is no longer available, focusing on the emergence and efficiency of pseudo Preferred Retinal Loci (pPRLs) during reading with a simulated scotoma. The study addresses a key question of this dissertation: how do oculomotor behaviour adapt to support reading when foveal vision is lost?

Using gaze-contingent eye tracking, I analysed fixation patterns to identify the spatial location of post-training, newly adopted fixation strategies (pPRL). By applying clustering techniques to the distribution of fixations across trials, several distinct pPRL configurations were identified – and they yield significant differences in reading efficiency.

The results show that pPRL establishment is not uniform across individuals but reflects an active process of adaptation. Readers explore different eccentric locations before stabilizing one or several pPRLs, suggesting that the development of eccentric reading strategies is both flexible and experience-dependent, even when displaying the very same simulated scotoma to all individuals. This study provides insight into the oculomotor mechanisms that allow readers to compensate for pathological foveal vision loss, contributing to a more integrated understanding of reading adaptation under central visual field loss.

These preliminary results highlight key trends in oculomotor adaptation that will be examined in greater depth through subsequent analyses.

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1 Introduction

Reading with central vision loss requires a profound reorganization of eye movement control. When the fovea can no longer provide detailed vision, individuals must learn to use a *Preferred Retinal Locus* (PRL) – an eccentric area of the retina that substitutes for the damaged fovea as the new reference point for fixation (Crossland et al., 2005; Tarita-Nistor et al., 2023). PRLs can form either above, below, or beside the scotoma, and their establishment is typically slow and variable across individuals and tasks (Crossland et al., 2005). Once established, a PRL can support relatively stable fixation, but reading performance usually remains slower and less accurate than foveal reading due to reduced acuity, increased crowding, and poorer contrast sensitivity (S. T. L. Chung, 2020). Recent work suggests that patients may develop multiple coexisting PRLs depending on the visual task, indicating a flexible and task-specific use of PRL (Crossland et al., 2005; Tarita-Nistor et al., 2023).

Training and perceptual learning can, however, lead to substantial improvements. Studies in patients with macular degeneration show that practice can strengthen the use of a PRL and increase reading speed (Maniglia, Cottureau, et al., 2016; Pijnacker et al., 2011). Comparable effects have been observed in normally sighted participants reading under a simulated central scotoma, where prolonged practice induces eccentric viewing behavior and measurable gains in reading fluency (Kwon et al., 2013; Maniglia, Pavan, et al., 2016; H. Yu & Kwon, 2023). This eccentric viewing behavior, developed through simulated scotoma exposure, involves the development of a PRL-like region, called a “pseudo-PRL” or “pPRL” (Rose & Bex, 2017). In the present chapter, we will use this term to describe the adaptation observed in healthy readers, as it is functionally similar to a true PRL but is not a product of a disease processes.

The present study extends this line of research by characterizing the oculomotor adaptations that accompany practice under simulated central vision loss. Specifically, we investigate whether and how readers develop stable pPRL strategies during training, whether some of these strategies lead to better reading efficiency, and how linguistic and visual properties of words modulate fixation patterns.

We address five main questions:

- Where do participants fixate relative to the words, and how does this change across practice?
- Do distinct pPRL locations emerge, and if so, which ones?
- Are some pPRL strategies more efficient than others?

Do fixation patterns vary across visual and psycholinguistic factors (position of the word on the screen, visual ambiguity, word length, orthographic similarity, word frequency, in-context predictability)?

Are there systematic differences between young and older adults in the establishment or stability of pPRLs?

2 Methods

Participants. Two groups of healthy adults took part in this study (Table 7.1): young adults (N = 22, 15 females; 19–28 years, M = 22.7 ± 2.4) and older adults (N = 16, 11 females; 63–74 years, M = 68.9 ± 4.1). All participants had normal or corrected-to-normal vision and no history of ocular disease.

Procedure. Participants read 304 sentences in a self-paced reading paradigm while their eye movements were recorded. During reading, a gaze-contingent scotoma occluded the central 10° of their visual field. Participants completed 19 reading blocks, allowing the analysis of both early and late practice stages.

Measures and preprocessing. Eye position data were converted to coordinates relative to the word center (0°, 0°), yielding fixation coordinates relative to each word’s center. For each participant and block, the center of gravity of fixation density was computed to summarize the location of a pseudo-Preferred Retinal Locus (pPRL) for that block. Blocks were labeled as “practice” or “trained” based on learning curves, described in the general methodology (Chapter 2). Reading time was extracted at the word level and log-transformed for statistical modeling.

Self-Paced reading paradigm	Sentence corpus	Experimental setup	Outcome measures
Healthy young adults reading with a simulated scotoma			
N = 22 (15F / 7M) Mean age = 22.7 (2.4)	Corpus #1 304 sentences	Computer screen + eye tracker	Reading time Fixation number Fixation position
Healthy older adults reading with a simulated scotoma			
N = 16 (11F / 5M) Mean age = 68.9 ± 4.1	Corpus #1 304 sentences	Computer screen + eye tracker	Reading time Fixation number Fixation position

Table 7.1. Summary of experimental groups included in this study, as well as the corpus, experimental setup and outcome measures. Nine participants (5 young; 4 older) who did not reach a learning plateau (see Chapter 2 Section 6.1.2 for details) were not included in this study.

3 Results

3.1 Progressive eccentric shift of fixation with training

Across practice, fixation density maps revealed a clear shift away from the word center, reflecting the gradual adoption of eccentric viewing in both groups (Figure 7.1). In early blocks, fixations clustered tightly near the word center. By late blocks, fixations shift vertically, forming dense peripheral zones consistent with adaptation and pPRL use. Still, a large amount of fixations remain on the word, revealing the tendency for a bimodal distribution during the last block. For younger readers, this clear bimodal distribution at block 19 suggests the adoption of a predominant top and/or middle fixation strategy. In older

adults, the pattern is less clear, possibly reflecting greater inter-individual variability or the smaller sample size in this group. To determine whether these eccentric fixations reflected distinct and stable pPRL locations at the individual level, we next applied a clustering analysis. And because we aim to better understand reading with a central scotoma, from now on, we will only focus on data collected once participants were trained to the presence of the scotoma. As described in detail in Chapter 2 Section 6.1.2, a learning curve was estimated for each healthy participant reading with a simulated scotoma. Average reading time was plotted as a function of block number. For each plot, we estimated the breakpoint(s) and derived a plateau of performance. All blocks included in this plateau showed stable reading time with reduced variability, leading us to consider the individual as “trained”. Only data from blocks within the plateau were included in the next analyses.

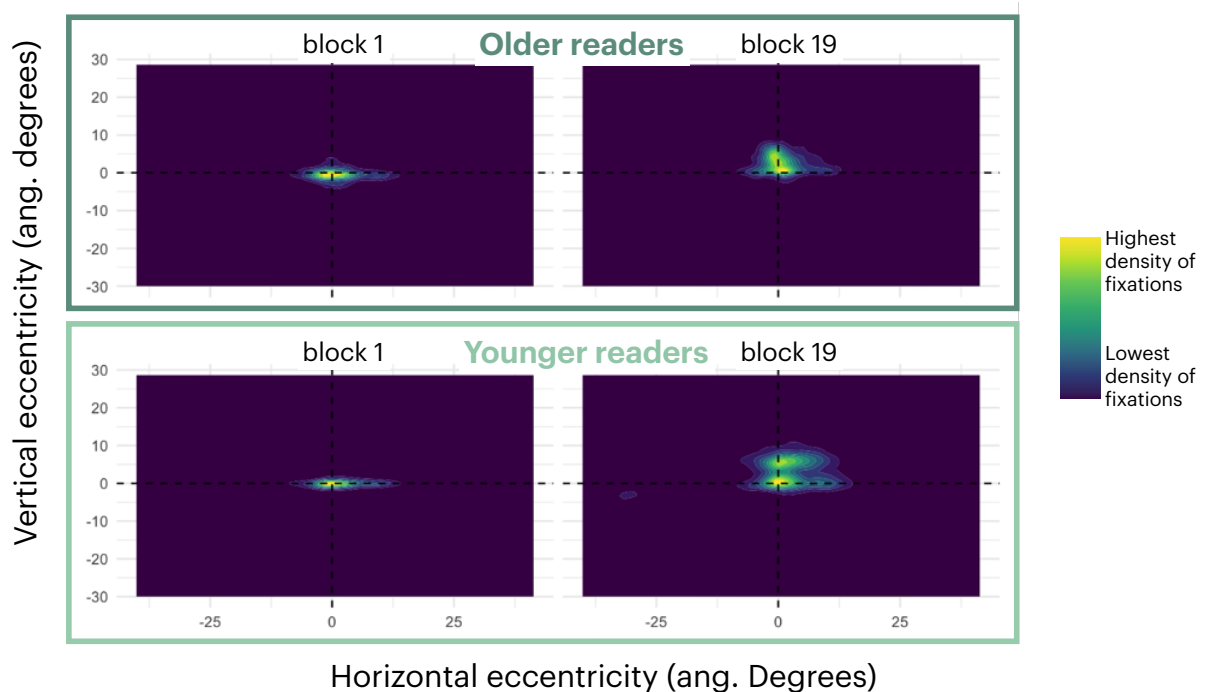


Figure 7.1. Evolution of fixation density mapped across all participants and broken down by block index (Block 1 vs. Block 19), in young and older adults. Each panel shows a 2D fixation density map relative to word center (0,0). Yellow indicates higher fixation density. Both groups progressively shift fixation away from the word center, consistent with the establishment of eccentric viewing.

3.2 Identification of distinct fixation locations

We ran Gaussian Mixture Modeling (GMM) on fixation peaks and identified four spatially distinct clusters (Figure 7.2), corresponding to fixation zones above, below, to the right of the word, and near the word center. First, we found that no participant used a right-sided pPRL (i.e., scotoma to the left of the word). Right fixations (red) represent peaks of fixation to the right of the word, indicating that words were read using the left pPRL. Bottom fixations (purple) indicate that words were identified using a top pPRL. The top fixations (blue) represent peaks of fixation higher than the word, indicating the adaptation of a bottom pPRL, as illustrated in Figure 7.3.

Older and younger readers pattern differed, as young readers did not show any bottom fixation cluster, whereas older readers showed very few right fixation cluster.

Fixations in the “mid” cluster (green) mean that, most of the time, participants in this group realized most of their fixation in this area. However, because the scotoma covered approximately seven to eight letters ($\approx 10^\circ$), these apparently central peaks cannot reflect true foveal viewing but rather an average of multiple eccentric fixations whose center of gravity fell near the word. This is why we decided to do a visual inspection and categorized participants’ strategies one by one.

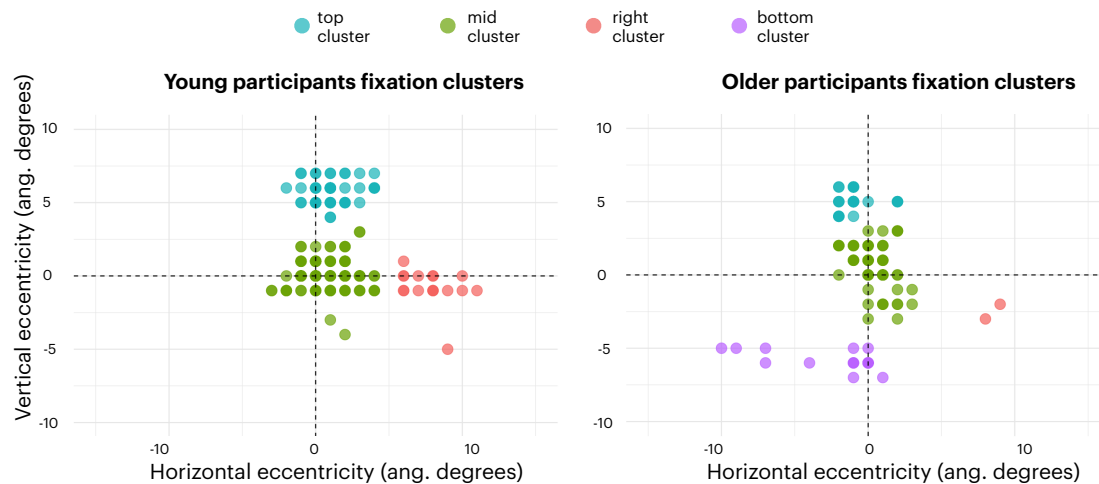


Figure 7.2. Cluster classification of fixation peaks across participants, for each blocks considered part of the trained phase. Colors indicate GMM-based fixation clusters. Four distinct spatial zones (top, mid, right, bottom) emerged consistently across participants, revealing identifiable eccentric fixation strategies.

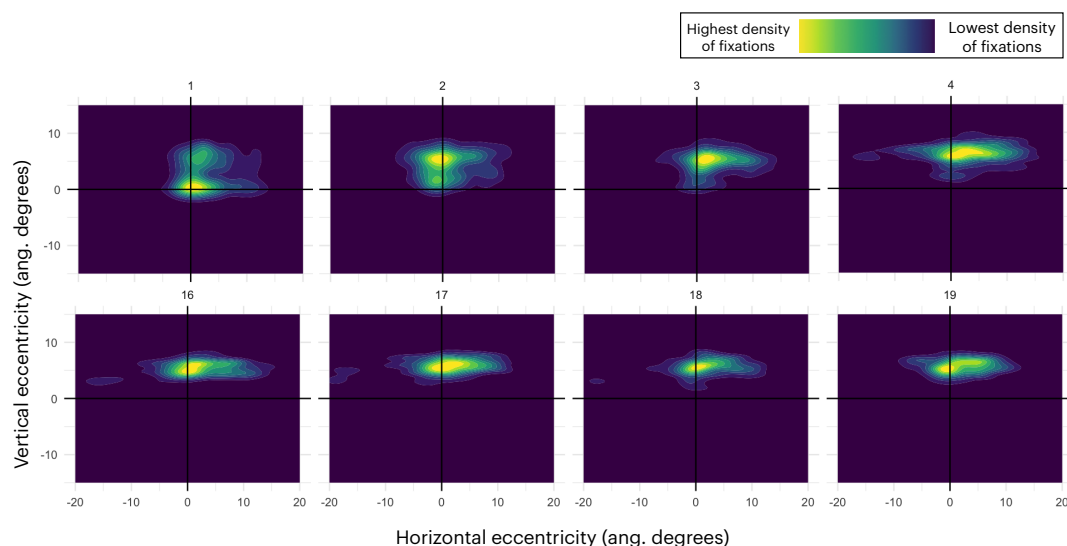


Figure 7.3 Development of a top fixation strategy (i.e., a bottom pPRL) in one participant. Fixation density maps are shown for the first (1-4) and last (16-19) four blocks of reading. Yellow indicates areas of high fixation density, and dark purple indicates areas of low fixation density. In the first block, most fixations fall directly on the word; by the second block, fixations shift above the word; and by block 4, none fall directly on the word, indicating that the top fixation strategy has fully developed. No clear change is observed from block 4 to block 19.

3.3 Manual classification of pPRL strategies

Among participants classified as mostly fixating on the word (“mid cluster”), we detected different type of misidentified strategies, that are presented in Figure 7.4 (top panel). In subjects A and B, the highest fixation density (i.e. yellow) is located on the word center. However, there are also a lot of other fixations (i.e. darker colors) that do not land directly on the word. These other fixations are not as precise and thus, do not come up as the highest density peak. It seems that both participants have multiple pPRLs – subject A has a high density of fixations to the right of the word, indicating a left pPRL and subject B has a high density of fixations landing to the top of the word, indication a bottom pPRL. Subjects A and B have been reclassified manually, respectively as vertical and horizontal strategies. This allowed to test the efficiency of these different reading strategies. Subjects C and D represent the two other strategies found, respectively a bottom pPRL (top fixation) strategy and a top pPRL (bottom fixation) strategy.

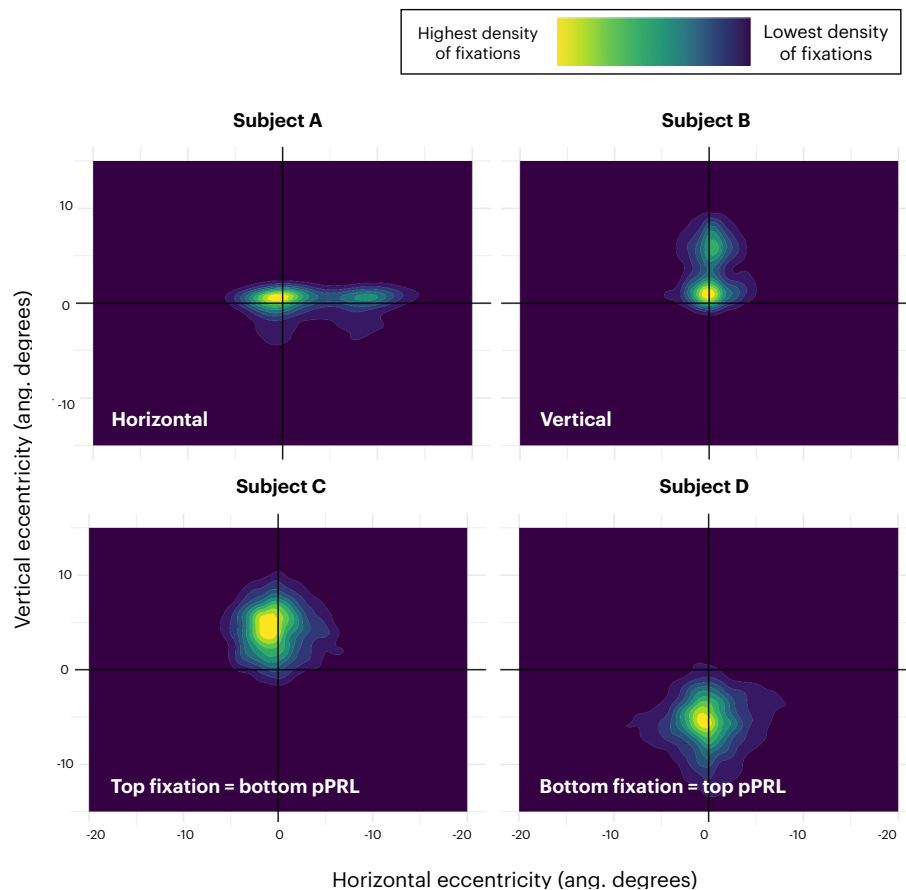


Figure 7.4. Fixation position on the screen with regards to the word position. Each plot corresponds to the fixation position of one participant, across all blocks of reading considered part of the trained phase. Each subject represents one strategy observed in this study. Subject A corresponds to a horizontal strategy (fixation position varies from center to right of the word), subject B corresponds to a vertical strategy (fixation position varies from top to center of the word), subject C corresponds to a bottom pPRL (only one fixation cluster to the top of the word) and finally, subject D corresponds to a top pPRL (only one fixation cluster to the bottom of the word).

3.4 Efficiency of pPRL strategies

Once reading strategies were reclassified by hand, a linear mixed-effects model was fitted to assess the effects of fixation position and age group on reading efficiency (log-transformed word reading time (RT)). The model revealed significant main effects of fixation strategy and group, as well as significant interactions between the two factors (Figure 7.5 and Table 7.2).

Older readers using a bottom pPRL, showed significantly longer reading time (mean predicted RT = 2.62 s) than the ones using a top pPRL (mean = 1.58 s, $t = -2.765$) or a vertical strategy (mean = 1.72 s, $t = -2.551$). Reading time when using a horizontal strategy did not differ significantly from using a bottom pPRL ($t = -1.052$).

In the reference condition, which corresponds to the use of a bottom pPRL, young participants read significantly faster than older simulated readers (mean predicted RT = 1.25 s vs 2.61 s for older adults; $p = -4.663$). The significant advantage yield by the use of a top pPRL found in older adults was not present in young adults, who exhibit non significantly different reading time with any of the pPRL location (cancelation of estimates: $-0.4179 + 0.5869$ and $-0.5057 + 0.4962$). This indicates that the strategy benefits found in older simulated readers were largely absent in the younger group, whose reading performance remained relatively stable regardless of fixation position (respectively, bottom strategy: 1.24 s, top strategy: 1.25 s, horizontal strategy: 1.39 s and vertical strategy: 1.48 s).

	Estimate	SE	t-value
(Intercept) (bottom pPRL)	0.9629	0.1295	7.435
Older adults:vertical	-0.4179	0.1638	-2.551
Older adults:top pPRL	-0.5057	0.1829	-2.765
Older adults:horizontal	-0.2157	0.2051	-1.052
Young adults (bottom pPRL)	-0.7390	0.1585	-4.663
Young adults:vertical	0.5869	0.2018	2.908
Young adults:top pPRL	0.4962	0.2326	2.133
Young adults:horizontal	0.3235	0.2598	1.245

Table 7.2. Summary of the linear mixed-effects model assessing the effect of fixation strategy and age group on reading efficiency (log-transformed word RT). The reference condition corresponds to older simulated readers using a bottom pPRL.

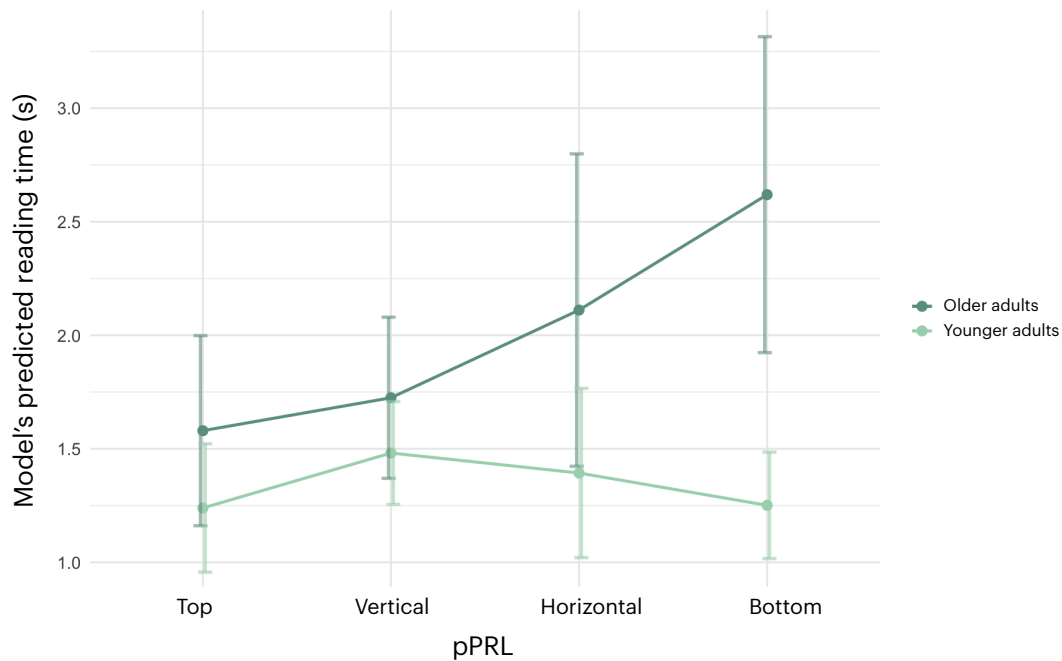


Figure 7.5. Predicted reading time (in seconds) grouped by fixation strategy and age group, based on the linear mixed-effects model presented in Table 7.2. Reading time was back-transformed from the log scale and is expressed in seconds. Error bars represent the 95% CI for the predicted reading time.

3.5 Influence of visual and psycholinguistic factors on the pPRL

Exploratory analysis of per-factor fixation maps revealed several consistent regularities.

Visual factors: Long words (10–12 letters) produced horizontally elongated fixation clusters, while short words (1–3 letters) generated compact, circular patterns. This effect appeared in nearly all participants, regardless of age. We believe that this horizontal elongation of the fixation area did not reflect a change in fixation strategy: the vertical position of the PRL remained constant across word lengths, indicating that readers did not shift vertically when processing longer words. Instead, the horizontal spread arose from multiple successive fixations made along the same pPRL position to encompass the full extent of the word. As for WAM, there is no reliable visual pattern suggesting that it modulates fixation location or pPRL use in either group.

Word position: A systematic lateral bias was observed, depending on the position of the word on the screen – left, center or right. For words appearing in the left region of the screen, fixations were shifted rightward relative to the word center; for words on the right, fixations shifted leftward (Figure 7.6). The mixed-effect model summarized in Table 7.3 shows that the position of the word on the display impacts the horizontal eccentricity in both young and older readers (left panel), however it does not affect the vertical eccentricity of fixations (Figure 7.7).

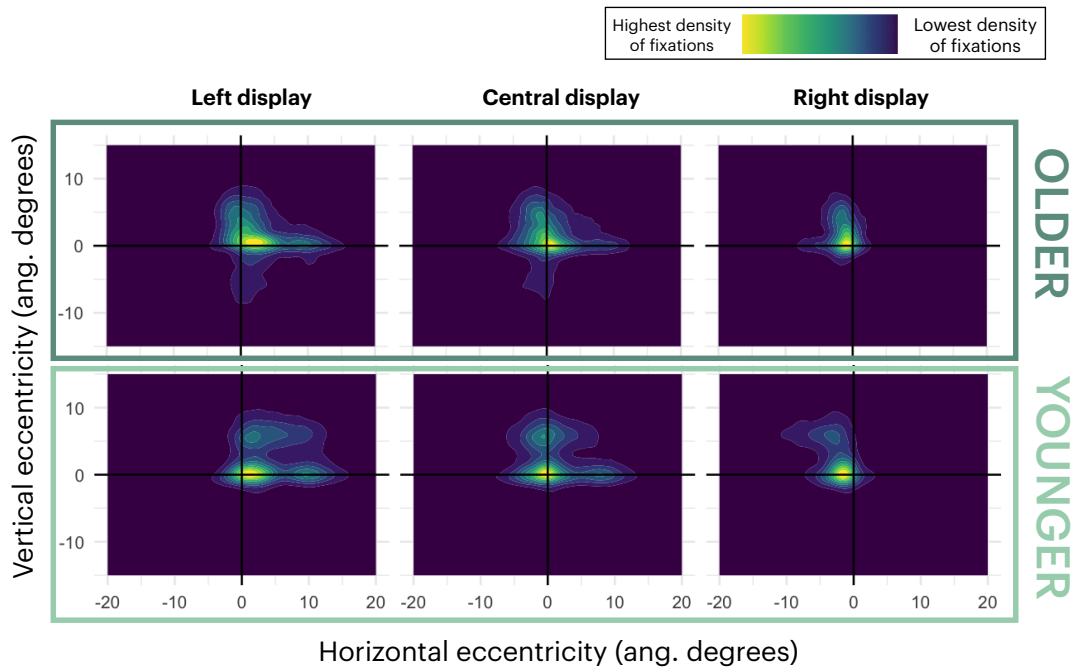


Figure 7.6. Overall fixations for the blocks of reading that are part of the trained phase, for older (top panel) and younger (bottom panel) readers, separated into words that were displayed to the left of the screen (left panel), center of the screen (central panel) or to the right of the screen (right panel).

	Estimate	SE	t-value	***
(Intercept)	1.7732	0.4878	3.635	***
center	-2.0952	0.3027	-6.921	***
right	-3.8880	0.3178	-12.235	*
Young	1.5311	0.6098	2.511	.
Young:center	-0.6401	0.3653	-1.752	***
Young:right	-1.9579	0.3875	-5.052	

Table 7.3. Summary of the linear mixed-effects model assessing the effect of word position on the screen on the horizontal shift of fixations. The reference condition corresponds to older adults reading words on the left of the screen.

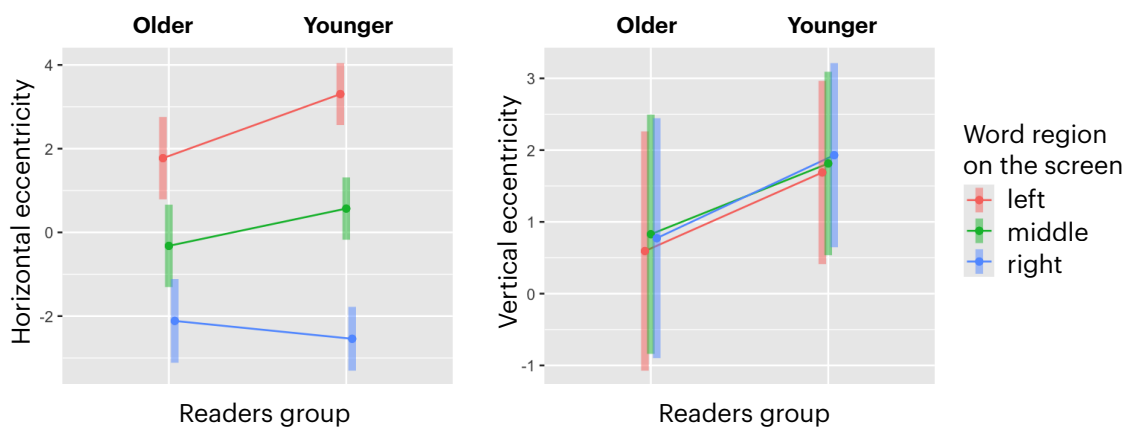


Figure 7.7. Model-predicted fixation position, depending on the position of a word on the screen (left/center/right), for older and younger readers. Left panel shows the result of the model presented in Table 7.3– the effect of word region on horizontal fixations eccentricity. Right panel shows the result of a second model – the effect of word region on vertical fixation eccentricity.

Psycholinguistic factors: The pPRLs or reading strategies do not seem to change depending on a word's predictability nor frequency property. However, it seems as though patterns of fixation evolve depending on whether a word was easy or hard to recognize. Figure 7.8 shows patterns for three representative participants. Regardless of their pPRL, the fixation density is scattered across a larger area: the easier a word is to read, the more scattered the fixations.

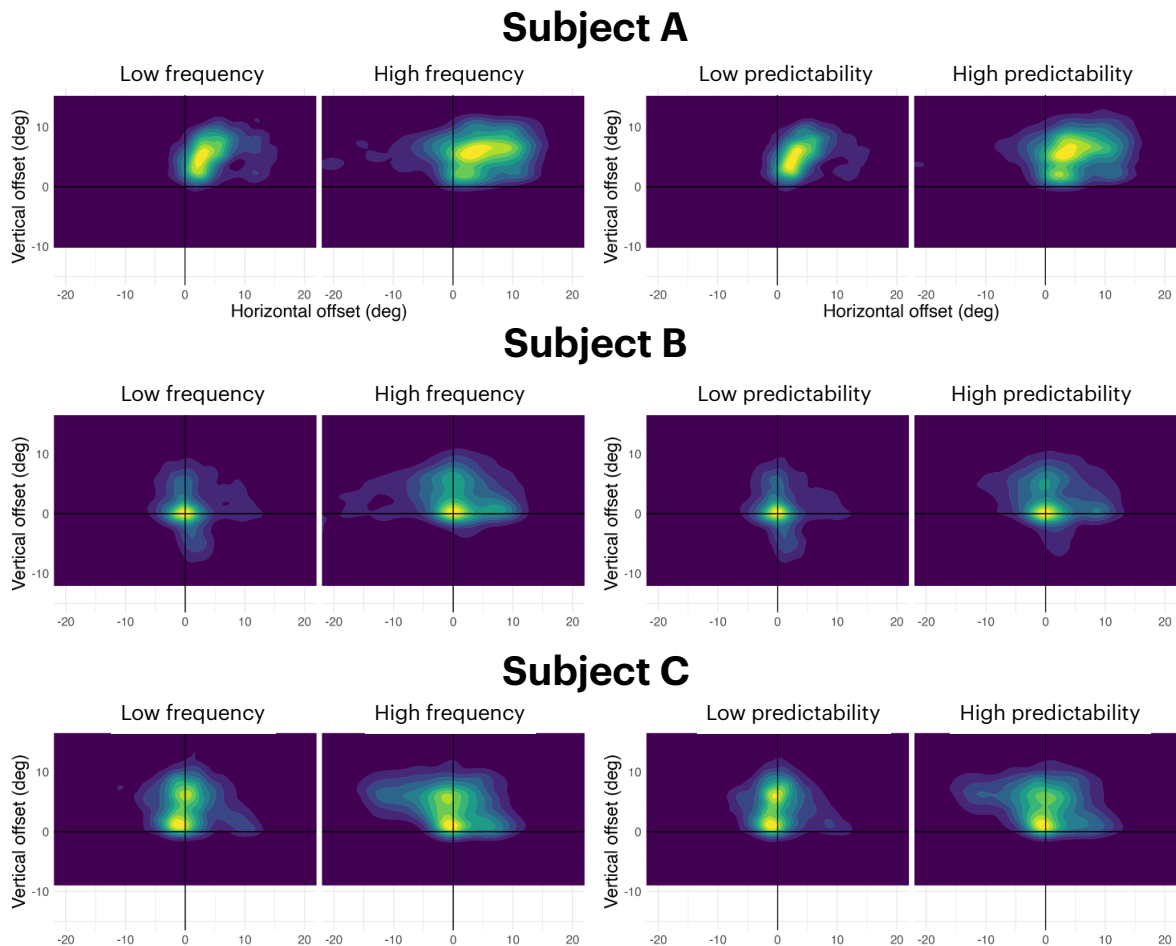


Figure 7.8. Example of three participants' fixation positions for blocks of reading that are considered part of the trained phase. Fixation densities were split between low and high frequent words in a first analysis (left panel), and between low and highly predictable words in a second analysis.

4 Discussion

This study examined how young and older adults adapt their eye movements when reading under simulated CVL. By analyzing fixation behavior over training, we characterized the emergence, efficiency, and modulation of eccentric viewing strategies, or pPRLs. The results revealed clear evidence of eccentric adaptation and substantial interindividual diversity in pPRL location.

Eccentric adaptation and PRL development

The observed eccentric shift of fixations across practice replicates prior evidence that gaze-contingent scotoma simulation leads to rapid oculomotor adaptation (Kwon et al., 2013). Participants progressively shifted away from the word center and relocated fixation to a newly established pPRL. The variability of pPRL location across healthy individuals mirrors the diversity of PRL observed in patients with macular degeneration (Crossland et al., 2005; Tarita-Nistor et al., 2023), even though they were all presented with the same central mask. This result alone suggests that the characteristics of the pathological scotoma (size, shape, position) are not the only determinants of the PRL location.

PRL location and efficiency

In this study, we reported significant difference in performance depending on the location of the pPRL, but only for the older group of participants. In the younger group, no significantly higher performance was found for a specific pPRL location. This is not in line with previous results from (Prahalad & Coates, 2020) who reported that reading speed was higher when subjects used a pPRL below the scotoma rather than the left or right of the scotoma. One major difference between their report and ours, is that their participants were trained to use all pPRL positions tested (to the right, to the left, and below the scotoma). With such paradigm, these authors were able to compare performance across pPRL position within each participant, cancelling out inter-individual differences, possibly explaining part of the discrepancy.

Another interesting observation from our own results, was that none of our participants adopted a pPRL to the right of the scotoma. This result is in line with many previous studies reflecting a general aversion to a rightward PRL (see Prahalad & Coates, 2020 for a review). This could be explained by the natural left-to-right dynamics of reading in French, combined with the persistence of the saccadic reflex. For each new fixation, saccades are programmed towards the center of the next target, thus masking the word. Individuals then make corrective saccades to reveal the word, typically toward the right side – consistent with the direction of natural reading movements. Adopting a right PRL would therefore require suppressing this well-established oculomotor pattern and fixating “backward” after the initial saccadic reflex, which is counterintuitive. This hypothesis is backed up by recent evidence from (Prahalad & Coates, 2020) who reported a characteristic back-and-forth eye movement pattern for all subjects using a right pPRL. While one could argue that a right PRL could be effective if explicitly trained, as it would rely on the right visual field that normally receives most attentional resources during left-to-right reading, results from (Prahalad & Coates, 2020) suggest that a right PRL yields automatic and compulsory eye movements that are non-optimal, possibly explaining why patients avoid a right PRL.

In our experiment, participants were not guided toward one strategy or another. They were only instructed to read as fast and as accurately as possible. Thus, the observed strategies at the end of training emerged spontaneously. The lack of significant efficiency differences across PRL types suggests that several spatial solutions can sustain comparable reading performance once stabilized. This, again, supports the idea that PRL selection is constrained

by individual perceptual and oculomotor preferences rather than by a universal optimal location. Comparable flexibility has been reported in studies of eccentric reading training (Barraza-Bernal et al., 2017). In patients, where scotomas are often irregular and asymmetrical, PRL selection is likely even more constrained by the unique topography of visual field loss, further reinforcing this individual variability.

Multiple PRLs: combining oculomotor re-referencing and attentional hypothesis

Despite the obvious shift in fixation position towards an eccentric location, which reflects the adoption of a pPRL, we also observed a persistent pattern of fixations falling onto the word. We interpret this as the persistence of the saccadic reflex. Even though the foveal region no longer provides useful visual input under simulated CVL, as they progress through text, participants continue to program saccades toward the next target (i.e., word), as they would under normal viewing. They then make corrective saccades to reveal the word. According to the oculomotor hypothesis, complete adaptation of the oculomotor system would involve at least two different reorganization mechanisms: (1) one to achieve eccentric fixation and (2) one to reorient the control of saccades around the PRLs' coordinates. Our results point to the evidence that the establishment of a pPRL does not involve a re-programming of the saccades towards the pPRL position. Although already documented in the literature, this result highlights the fact that despite its obvious interest when studying CVL, adaptation to a simulated scotoma does not allow to yield profound oculo-motor reorganization.

Yet, our findings highlight the development of one or multiple pPRLs in just a few hours of reading under a simulated central scotoma. Interestingly, pPRL use remained dependent on other visual factors, such as the position of the word on the screen: the oculomotor system appears to develop and use the pPRL as a stable reference while remaining flexible to the position of each word. This dual influence is consistent with the coexistence of two possible mechanisms: an oculomotor re-referencing process, where fixation control shifts to a new eccentric area (White & Bedell, 1990), and an attentional hypothesis, where attention moves within and around the PRL depending on the word characteristics. Both mechanisms likely contribute jointly to the optimization of reading performance under central vision loss.

Influence of linguistic and visual factors

pPRLs were relatively stable across all psycholinguistic predictors, except for word length. Indeed, fixation maps showed that longer words yielded more horizontally elongated fixation clusters than short words, but their vertical position remained unchanged. We believe that this change in horizontal fixation position does not reflect the emergence of a new pPRL, but rather the flexible use of the same pPRL across the longer word. In this sense, word length influences the spatial extent of fixations without modifying the established PRL location.

Although our exploratory fixation maps revealed several regularities – such as horizontal elongation for longer words – most linguistic and visual variables appeared to exert only subtle influences on pPRL use. Word frequency and predictability affected the dispersion rather than the location of fixations: easier words (i.e. highly frequent, highly predictable) produced more scattered fixation patterns, possibly reflecting a greater reliance on a fast

coarse-grained lexical processing described in (Grainger & Ziegler, 2011)'s model of reading. On the other side, harder words (i.e. rare, non-predictable), which might not be identified through the coarse lexical route, yielded tighter fixation clusters which could be consistent with the fine-grained, letter-specific processing.

In addition, neither visual ambiguity (WAM) or word length produce any reliable spatial modulation of the pPRL, suggesting that small letter-level confusability differences or length altered fixation placement once a stable reading strategy has developed. Overall, if psycholinguistic or visual factors modulate pPRL behavior, their effects are likely subtle, requiring statistical testing rather than visual inspection. Furthermore, given the strong influence of word position on horizontal fixation eccentricity, it remains possible that higher-order interactions – such as frequency*word position or predictability*word position – could reveal localized adaptations of pPRL use that would be dependent on psycholinguistic or visual characteristics of words. Future analyses should therefore examine these interactions to determine whether the oculomotor system dynamically integrates linguistic difficulty with spatial constraints during eccentric reading.

5 Perspectives and conclusion

Together, these findings provide a detailed account of how eccentric fixation strategies emerge and stabilize with practice. The present study offers a first step toward quantifying individual differences in pPRL development and reading efficiency under simulated central vision loss. However, several open questions remain.

Future analyses should further examine the interaction between pPRL position and psycholinguistic difficulty, investigate why some participants establish a pPRL rapidly while others never fully stabilize, and quantify whether participants who show less dispersion of fixations – indicating a more stable pPRL – also achieve faster or more consistent reading times.

General discussion

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This dissertation aimed to understand how reading processes adapt when central vision is lost. Across the different studies presented in this manuscript, I examined how visual and psycholinguistic factors jointly affect reading performance, and how readers develop adaptive eye-movement strategies when foveal vision is unavailable.

Together, the results show that reading under CVL highly relies on the psycholinguistic content of text, which helps the reader predict and recognize words even when the input is degraded.

1 Summary and interpretation of key findings

1.1 Psycholinguistic constraints in simulated central visual field loss

In Chapter 3, I examined the effect of in-context predictability on reading with a simulated central scotoma. The main finding was that predictable words were read faster than unpredictable ones, and this facilitation was stronger when central vision was masked. This result suggests that readers rely more heavily on linguistic context when visual information is unreliable.

In Chapter 4, I focused on orthographic similarity. I compared classical and newer metrics such as Coltheart's N and OLD20. Results showed that large orthographic neighborhood, which normally helps recognition by speeding lexical access in healthy reading, can instead slows reading under simulated CVL. This reversal indicates that when letters are hard to recognize, similar word forms compete with each other, making recognition more difficult.

When considered together, the results from Chapters 3 and 4 indicate that, under simulated CVL, visual information becomes less reliable while linguistic context becomes increasingly useful. In other words, readers compensate for degraded visual input by relying more on psycholinguistic prediction to maintain reading fluency. Predictability helps compensate for

visual uncertainty, whereas excessive orthographic similarity increases confusion. This highlights the complementary roles of top-down (linguistic) and bottom-up (visual) mechanisms in maintaining reading performance when central vision is impaired.

These results also raise an important question about adaptation: the larger facilitation by predictability and the reversal of the neighborhood effect both suggest that linguistic and visual systems adjust their relative weight depending on visual reliability. This may reflect a general compensatory principle of reading with CVL: when bottom-up input is uncertain, top-down knowledge takes over to preserve reading performances.

1.2 Visual ambiguity: new measures of word-level confusability

Chapter 5 introduced two new measures designed to better capture the visual ambiguity of words: the Word Ambiguity Measure (WAM) and VA20. These measures were based on the visual overlap between letters and words, rather than on spelling distance only.

The WAM and VA20 metrics addressed a limitation of classical measures such as OLD20, which consider letter substitutions but ignore the actual visual similarity between letter shapes. By quantifying pixel-level confusability, these new metrics offer a more realistic way to evaluate how easily letters or words can be confused in peripheral vision.

The analyses showed that visual ambiguity, as captured by WAM and VA20, contributes to reading performance independently of lexical variables such as frequency or predictability. This result suggests that visual appearance itself plays an important role when reading with eccentric vision. These measures thus provide a methodological bridge between visual psychophysics and psycholinguistics and could be reused in future studies or clinical assessments of reading at the word level.

1.3 Reading across age and visual profiles

After establishing visual and linguistic determinants of eccentric reading in young adults, Chapter 6 extends the question to different populations, to examine whether age or pathological visual loss modulates these effects.

To address this question, I compared reading performance across three populations: young adults with simulated scotoma, older adults with simulated scotoma, and older adults with pathological central vision loss.

Across all groups, frequency and predictability remained strong predictors of reading time, confirming that linguistic cues continue to support word recognition under degraded vision. However, the efficiency with which these cues were used differed between populations. Daily readers and simulated readers relied most on linguistic information, while patients who had stopped reading tended to use slower, length-based strategies. These results suggest that

sustained reading habits helps maintain efficient, linguistically driven reading, whereas reduced reading habits limit the ability to exploit psycholinguistic cues of text.

In healthy readers trained with a simulated scotoma, age affected the speed rather than the nature of adaptation: older simulated readers followed the same pattern as younger ones but progressed more slowly. Overall, these results suggest that perceptual plasticity is preserved, even though reduced in magnitude.

These results show that reading efficiency under pathological central vision loss depends on how well readers can use linguistic cues to compensate for visual degradation. Psycholinguistic compensations were more efficient in daily readers. To understand how such compensations develop, the next chapter (Chapter 7) examines the underlying oculomotor adaptations – specifically, how readers reorganize their fixations and develop new Preferred Retinal Loci (PRLs).

1.4 Oculomotor adaptation and PRLs

Chapter 7 investigated how readers develop pseudo Preferred Retinal Loci (pPRLs), when reading with simulated scotoma. Using fixation clustering analyses, I identified several typical reading strategies and showed that some strategies are more efficient than others. For instance, in older simulated readers, bottom and vertical fixation strategies were associated with shorter reading times than top fixations. This finding suggests that the spatial position of the PRL influences how efficiently words are processed in peripheral vision.

These findings align with previous patient studies showing that practice leads to stabilization of a pPRL and improved reading performance. Together, they support the idea that PRL development reflects an active process of adaptation in which the oculomotor system reorganizes to use remaining functional retina. In addition, I found many participants to have developed multiple pPRLs, which is consistent with what is found in the literature.

Overall, the results of Chapters 3 to 7 form a coherent picture of adaptation: psycholinguistic, visual, and oculomotor adjustments work together to try and maintain reading when central vision is compromised. The following sections discuss the implications of these findings for reading rehabilitation, and the methodological challenges associated with studying these processes.

2 Theoretical and practical implications of the findings

The studies presented in this thesis converge toward a common idea: impaired reading from central visual field loss is not purely a visual problem. It is a multifactorial process in which visual, psycholinguistic, and oculomotor components interact continuously.

2.1 Implications for existing theories and models of reading

Table 1.2, presented in Chapter 1 summarized how major reading models account for the effects of frequency, predictability, and orthographic neighborhood. Comparing these theoretical predictions with the present results helps clarify how existing models of reading, most of which were designed for normal foveal vision, extend – or fail to extend – to reading with CVL.

Frequency

All models of reading predict that high-frequency words are recognized faster because their representations are more easily activated. The Logogen and Interactive Activation Models posit that frequency lowers the activation threshold. In the Dual-Route and Coarse/Fine models frequent words follow a faster lexical route. And in models of oculomotor control (E-Z Reader, SWIFT, and OB1-Reader), frequency speeds lexical processing by shortening fixation duration and increasing skipping rate.

Our results confirm this prediction: frequency remained a strong facilitator of reading under both simulated and pathological CVL. This suggests that the mechanisms linking frequency to lexical activation are preserved even when visual input is degraded.

Predictability

Some models posit contextual facilitation, though its source differs. In the Logogen framework, facilitation arises through priming: activation spreads from previously encountered or semantically related words that pre-activate corresponding logogens. In contrast, E-Z Reader, SWIFT, and OB1-Reader implement sentence-level predictability, where contextual constraints accelerate lexical access.

Across all experiments, contextual predictability also improved reading efficiency, and this effect was even stronger under simulated scotoma. These findings are therefore consistent with models that assume top-down activation from context and show that such mechanisms become more influential when visual (i.e. top-down) evidence is reduced or degraded.

Orthographic neighborhood

In normal vision, the IAM and OB1-Reader models predict that words with many orthographic neighbors should benefit from co-activation of similar forms for words of low frequency, producing faster recognition. In contrast, our results showed that large neighborhoods slowed reading when visual input was degraded. This suggests that, under uncertainty, competition between similar words outweighs facilitation – consistent with the inhibitory component present in the dual route cascade model. Yet, given the large dependence of the orthographic neighborhood effect on the characteristics of the neighbors themselves, it remains to be tested how orthographic neighborhood influences eccentric reading when taking into account all the neighbors features (frequency, visual ambiguity, ...).

Integrating visual and linguistic constraints

Taken together, these results support the general architecture of existing models but show that the relative weight among their components changes when visual reliability decreases. Frequency and predictability effects follow the same direction as in normal reading, whereas orthographic competition becomes more costly. Reading with CVL therefore appears to rely on the same interactive principles described by current models of normal reading, but with a reweighted interplay between visual, lexical and contextual information.

From a theoretical point of view, the results call for more integrated models of reading that include both visual quality and psycholinguistic predictors. Existing computational models of reading could be expanded to account for the degraded visual input and compensatory mechanisms observed in CVL.

2.2 Implications of the findings for reading rehabilitation

From a practical perspective, these findings support the development of rehabilitation strategies that extend beyond visual aids such as magnification or contrast enhancement. Linguistic simplification – using high-frequency, orthographically distinct, and contextually predictable words – can reduce reading difficulty in individuals with central vision loss.

In addition, encouraging daily reading activity with simplified text may further support the development and stabilisation of one or more PRL, a key adaptive strategy for eccentric reading. Indeed, sustained reading practice has been shown to improve fixation stability and increase reading speed even without changes to acuity or PRL location (Chung, 2011; Tarita-Nistor et al., 2009). These findings indicate that simplified materials can serve not only as compensatory aids but also as a form of perceptual learning to sustain functional reading in low vision.

Beyond clinical or experimental settings, simplified materials could also be used for leisure reading, offering a low-effort way to reinforce oculomotor strategies through engaging content. By engaging with content that is both accessible and enjoyable, individuals with CVL may reinforce adaptive eye-movement strategies and preserve reading fluency over time without perceiving the activity as rehabilitation. This dual benefit – supporting autonomy while fostering oculomotor adaptation – makes linguistically simplified reading material a promising tool for sustaining reading habits across contexts.

3 Methodological constraints in the study of eccentric reading

3.1 Clinical and methodological challenges in patient study

Investigating the text constraints on reading in patients with central visual field loss presents several practical and scientific challenges.

First, patient populations are heterogeneous. CVL can result from a variety of diseases. And even within a single macular pathology, the size, shape, and density of the scotoma can vary greatly from one patient to another. Accurately characterizing these features requires specialized testing such as microperimetry or scotoma topography, which must be performed in addition to the experimental protocol and is not available in every study.

Another difficult variable to control is the time since the onset of CVL. Patients often cannot pinpoint when the binocular scotoma first appeared, yet this information is important because the stage of the disease influences the development of a PRL which consequently affects reading performance. Ocular status adds further complexity: some patients have a monocular scotoma, others have quite similar binocular defects, and others have large differences in binocular scotoma, all of which can affect binocular reading strategies.

Beyond these clinical factors, data collection itself is complex. Reading is a visually demanding task, and many patients fatigue quickly, limiting the number of sentences that can be presented in a single session and reducing the total amount of data per patient. Clean eye-movement recordings are particularly challenging to obtain when central vision is unavailable. Because fixation is often unstable in CVL, eye-tracker calibration is less reliable, and the recorded gaze positions may be inaccurate or imprecise. Furthermore, even with good calibration (performed using one PRL), the use of multiple PRLs make recorded data almost impossible to interpret.

Together, these issues make it difficult to recruit large, homogeneous cohorts and to obtain precise eye-tracking measures, all of which complicate the study of reading mechanisms in patients with central visual field loss. This is why, more recently, gaze-contingent simulated central scotoma paradigms have become a cornerstone for investigating how individuals adapt their eye movements and reading strategies in the absence of central vision.

3.2 Limitations of simulated central scotoma paradigms

Despite these advantages, a simulated scotoma does not fully reproduce the condition of an acquired central visual field loss. Most importantly, the fovea itself remains anatomically intact: the gaze-contingent mask simply hides the central region of the stimulus, so participants are aware of the scotoma and can still perceive its position.

In acquired CVL the retinal tissue is damaged and produces a true absolute scotoma, which is typically not consciously seen. Because the fovea is still intact, the brain may handle

attention and eye movements in ways that differ from patients with acquired CVL (S. T. L. Chung & Legge, 2025).

The adaptation process also differs profoundly. Patients with macular disease experience a gradual loss of foveal input, often over months or years, allowing time for cortical reorganization and the spontaneous development of a PRL. By contrast, normally sighted participants are suddenly exposed to the scotoma (usually around 10° diameter) and for a limited duration. Any strategies they adopt are short-term compensations rather than long-term changes.

Finally, simulation cannot reproduce the emotional and motivational context of real vision loss. Patients face permanent impairment, and lifestyle changes that influence attention, fatigue, and daily reading practice - factors that are impossible to capture in a short laboratory session.

For these reasons, simulated scotomas are best viewed as a complementary model: they allow precise experimental control and insight into early compensatory strategies, but findings must be interpreted cautiously when extrapolating to the long-term adaptations of patients with central field loss.

4 General conclusion

This dissertation investigated how visual and linguistic factors jointly shape reading when central vision is lost. Overall, this work demonstrates that reading with central vision loss depends on a dynamic interaction between what can be seen and what can be expected from language. Understanding this interaction not only improves theoretical models of reading but also informs practical solutions for maintaining reading ability in people affected by macular disease.

The work presented in this dissertation brings together two research fields: psycholinguistics and low-vision psychophysics. By examining how linguistic and visual factors interact during reading under central vision loss, this thesis helps bridge the gap between these fields. It shows that the difficulties experienced by individuals with central field loss are not only visual but also linguistic, and that both levels must be considered to understand and support reading.

Beyond the individual studies, the thesis introduces new visual ambiguity measures (WAM and VA20), provides comparative evidence across simulated and pathological populations, and identifies adaptive fixation strategies that can inform rehabilitation. Together, these advances contribute to a more integrated view of reading as a flexible, multi-level process, and open new perspectives for designing accessible texts and personalized reading training for individuals with low vision.

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