Adult age differences in early word processing: Evidence from eye movements during sentence reading

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Abstract

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This thesis reports seven experiments which examine whether young and older adult readers differ in aspects of early word processing during reading. Further, this thesis explores whether the mechanisms underlying these processes differ between young and older adult readers. Despite age-related reading difficulties being well documented, little is known about the mechanisms underlying these difficulties. Many aspects of older adults' processing have not previously been examined in detail. Accordingly, the current experiments provide a novel examination of various aspects of older adults' early word recognition processing. Findings from Experiment 1 indicate that young and older adults make similar use of parafoveal orthographic information and have a perceptual span which is similar in size and symmetry. Experiments 2 and 3 revealed that older adults experience greater difficulty when reading low-contrast text than young adults. Further, Experiment 2 provided an initial indication that middle-aged readers do not yet experience the reading difficulty typically associated with older age. Experiments 4 and 5 suggest that young and older adults process letter position similarly (e.g. similar coding of "*problem*" and "*rpoblem*"). Experiments 4 and 5 also highlighted the potential for effects to be inflated in measures sensitive to rereading for groups that are more likely to reread. These groups may experience a "double-whammy" due to a greater likelihood of words being processed multiple times. Finally, Experiments 6 and 7 indicate that older adults may make more word misperception errors during reading when two words are both visually and orthographically similar and when the alternative reading of the word is higher frequency (e.g. mistaking "*spice*" for "*space*"). Overall, these experiments have advanced our understanding of adult age differences in early word recognition processes. These findings highlight key areas for development for future studies, models of eye movement control during reading and models of visual word recognition.

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List of Abbreviations

ANOVA = Analysis of variance

HFN = Higher frequency neighbour

LDT = Lexical decision task

LMEMs = Linear mixed effects models

M = Mean

SE = Standard error

TL = Transposed letter

WAIS-IV = Wechsler Adult Intelligence Scale- fourth edition

Chapter 1:

General introduction

1.1 Research background

Reading is a complex skill which takes substantial time and effort to acquire and involves the precise co-ordination and integration of a range of visual, oculomotor, and cognitive processes. Poor reading ability can have a profound impact on daily life, affecting academic success, employability and economic welfare. Therefore, it is of considerable concern that numerous studies indicate that older adults (aged 65 + years) experience reading difficulties in comparison to young adults (aged 18-30 years) (Kemper & McDowd, 2006; Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan, & Paterson, 2014; McGowan, White, & Paterson, 2015; Paterson, McGowan, & Jordan, 2013a,b; Rayner, Castelhano, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Yang, Castelhano, & Liversedge, 2011; Rayner, Yang, Schuett, & Slattery, 2013; Whitford & Titone, 2016; 2017) even in spite of adequate performance on standard tests of visual acuity. Despite these difficulties being well documented, little is known about the precise nature of adult age differences in reading or the mechanisms underlying these difficulties.

Accordingly, this thesis aims to further understanding of the nature of adult age differences in reading. These differences are assessed through a thorough examination of eye movement behaviour during sentence reading. More specifically, this thesis aims to examine whether young and older adult readers differ in aspects of early word recognition during reading and explore whether the mechanisms underlying these processes differ between young and older adult readers. The experiments in this thesis aim to gain an understanding of the following issues: parafoveal processing and the perceptual span (Chapter 2); the impact of reduced stimulus quality on reading (Chapter 3); letter position coding processes (Chapter 4) and word misperception (Chapter 5). Many of these issues are well-documented in young adults, and these results serve to inform the current experiments. Overall, this Chapter aims to provide an overview of current knowledge relating to the issues explored throughout this thesis and explain the rationale behind each experiment undertaken. Section 1.2 discusses age-related visual and cognitive declines relevant to reading. Section 1.3 provides an introduction to eye movements during reading. Section 1.4 introduces some specific issues relating to word recognition during reading. Section 1.5 discusses parafoveal processing during reading. All sections include reviews of work relating to both young and older adults. Finally, Section 1.6 summarises and provides an overview of this thesis.

1.2 Age-related visual and cognitive decline

To consider why reading performance may differ in older age, it is first important to consider the wider context of age-related changes that occur. A range of visual and cognitive declines occur with advancing age. These declines may contribute to the emergence of adult age differences in reading. Those declines which may be particularly relevant to the reading process are discussed here. Section 1.2.1 discusses key visual declines. Section 1.2.2 discusses key cognitive declines. Finally, Section 1.2.3 summarises Section 1.2.

1.2.1 Visual declines

Several subtle declines in visual abilities occur in advanced age arising from both optical and neural changes (Owsley, 2011). These changes may impair the ability of older adults to carry out the required processing to read quickly and accurately and so may contribute to the slower reading speeds and differences in eye movement behaviour (discussed in Section 1.3.2) seen in older adults compared to young adults.

Some of the key visual changes include a drop in high-contrast acuity during older age (Owsley, Sekuler & Siemsen, 1983; Crassini, Brown & Bowman, 1988; Laitinen, Koskinen, Härkänen, Reunamen, Laatikainen, & Aromaa, 2005) and a loss of sensitivity to fine visual detail (such as letter features or individual letters). This loss of fine-scale detail is in contrast to relatively intact sensitivity to coarse-scale information (Crassini et al., 1988; Elliott, Whitaker, & MacVeigh, 1990; Owsley et al., 1983). As a result older adults may rely to a greater extent than young adults on coarse-scale features, such as overall word shape or word length, to recognise a word (Jordan, McGowan & Paterson, 2014; Paterson et al, 2013 a,b, this may be particularly important in Chapter 3). The onset of these changes typically begins at around 40-50 years of age (Schefrin, Tregaer, Harvey & Werner, 1999; Owsley et al., 1983; Owsley, 2011), although it is not yet known whether differences in reading performance are present at this age. This issue is addressed in Chapter 3.

Additionally, older adults experience greater difficulty resulting from the effects of visual crowding (Scialfa, Cordazzo, Bubric, & Lyon, 2013). Visual crowding describes a phenomenon whereby letters are more difficult to identify when they are closely surrounded by other characters than when they are presented alone (Bouma, 1970; Townsend, Taylor, & Brown, 1971; example shown in Figure 1.1). This effect occurs primarily in parafoveal vision. It is possible that this crowding reduces the visibility of adjacent letters or words (or increases spatial interference among them), making it more difficult for older adults to determine the boundaries of individual letters, resulting in jumbling and slowing reading (this may be particularly important in Chapter 4). Further, older adults display changes in aspects of eye movement control, with declines seen in various areas such as visual vestibular responses as well as changes in saccade behaviour, such as increased saccadic delay times (Kerber, Ishiyama, & Baloh, 2006) and decreased saccadic accuracy (Huaman & Sharpe, 1993; Sharpe & Zackon, 1987). Though note that young and older adults show no differences in landing position within words (Rayner et al., 2006; Paterson, McGowan, & Jordan, 2013c).

B + CBA

Figure 1.1. An example of visual crowding. The “B” on the left can be recognised more easily than the “B” on the right.

These declines have important implications for understanding adult age differences in reading. In all experiments in this thesis, eligibility criteria stipulated that participants should have normal visual acuity (at least 20/40 at the screen viewing distance of 80cm). Visual acuity was assessed using an ETDRS chart (Ferris & Bailey, 1996). Further tests of visual acuity were carried out for contrast sensitivity, using a Pelli–Robson chart (Pelli, Robson, & Wilkins, 1988), and high- and low-contrast acuity was also tested at standard and distance range. In all experiments, the visual acuity and contrast sensitivity of the different age groups is reported. However, the current thesis focuses on group differences and further research will be required to uncover the precise contribution of these declines to different aspects of processing.

1.2.2 Cognitive declines

In comparison to visual declines, changes in cognitive function in healthy ageing are not well defined, but a range of typical changes are observed. During normal ageing a general slow-down in processing across a variety of domains occurs (e.g. Salthouse, 1985), and this may well slow the rate at which older adults read. More specifically, age-related changes in working memory function have been implicated as a key source of age-related deficits in a variety of cognitive tasks and are likely to limit older adults' comprehension of complex text. Working memory is a multidimensional cognitive construct and these age-related deficits have been considered in a variety of ways. Salthouse (1994; 1995; 1996) suggested that age-related deficits in working memory and other cognitive tasks can be explained in terms of a general slowing of information processing. While there is little disagreement that older adults are slower than younger in a variety of tasks, others (e.g. Park et al., 1996), however consider speed of processing and working memory as separate entities, each making a separate contribution to age-related cognitive deficits. Research with young adults (see Daneman & Merikle, 1996) and older adults (Schroeder, 2014) suggests that working memory plays a key role in language comprehension, and so older adults with lower working memory capacity may struggle with certain types of text, such as syntactically complex text (but see Van Dyke, Johns & Kukona, 2014). Older adults have also been shown to display a lack of inhibitory control and generally have greater difficulty ignoring distracting information (Hasher, Zacks & May, 1999). This may be relevant to some reading tasks.

In Experiments 6 and 7 (Chapter 5) performance on a variety of cognitive tests was considered. Cognitive abilities were assessed using the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), a screening assessment for detecting cognitive impairment, and an exclusion criterion of <26/30 was applied. In addition, working memory (forward and backward digit span) was assessed using the Wechsler

Adult Intelligence Scale (WAIS-IV). As well as considering the role of declining cognitive skills, it also important to consider areas where older adults show preserved performance, or even, a performance advantage, such as vocabulary skill (Brysbaert, Stevens, Mandera & Keuleers, 2016), as this may also play an important role in individual reading performance (see Section 1.3.2). In Experiments 6 and 7, vocabulary was also assessed using the WAIS-IV. The performance of young and older adults is compared, and in addition, individual scores are treated as co-variates in the statistical models.

1.2.3 Summary

Various visual and cognitive declines occur during the normal ageing process. This thesis primarily focuses on group differences. Further work will be needed to reveal exactly which visual / cognitive variables may be related to specific aspects of older adults' reading. Throughout this thesis, current findings regarding reading performance in older adults are discussed. These visual and cognitive declines may well contribute to the observed findings (see Sections 1.3.2, 1.3.6, 1.4.5 and 1.5.3). The potential role of visual and cognitive factors in reading performance is discussed further in the General Discussion (Chapter 6).

1.3 Introduction to eye movements during reading

Eye movements are an excellent tool for studying how words are recognised during reading (see Liversedge & Findlay, 2000; Rayner, 2009 for reviews). This section provides a general overview of the current knowledge regarding eye movements in reading. Section 1.3.1 examines the basic characteristics of eye movements during reading. Section 1.3.2 examines the characteristics of older adults' eye movement behaviour during reading. Section 1.3.3 summarises the basics of eye-tracking technology. Section 1.3.4 describes some key eye movement measures. Section 1.3.5 summarises some of the most prominent models of eye movement control during reading. Section 1.3.6 considers adult age differences in the context of models of eye movement control during reading. Finally, Section 1.3.7 summarises Section 1.3.

1.3.1 Basic eye movement characteristics

Contrary to what we generally perceive, the eyes do not move smoothly across the page when reading (Javal, 1879, cited in Huey, 1908), but proceed along each line of text in a sequence of high-velocity ballistic movements, called *saccades*, which serve to shift the point of gaze. These movements are interspersed with brief pauses called *fixations*, during these pauses the eyes are relatively stationary, and the reader acquires visual information from the text. An example eye movement record can be seen in Figure 1.2.

During reading, fixations last around 250ms on average (Rayner, 2009) and these fixations can either be first-pass (occurring when the word is first encountered) or rereading (fixations that occur on words that have been encountered previously). A subset of words may also be re-fixated, receiving at least two successive fixations (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989). Additionally, readers do not fixate all the words in text, but typically skip (go past without fixating) about 30% of words. Determining the location of each fixation is not a random process; fixations usually occur just to the left of the middle of a word (the “preferred viewing position”, Rayner, 1979).

The average saccade moves the eyes around 7-9 letters along in the text (Rayner, 2009). During these saccades, vision is suppressed and visual information is not acquired (Matin, 1974). Saccades are usually progressive (made in the forward direction), but a proportion, around 10-15%, are regressive, moving backward in the text either to resample a previously fixated word, or to fixate a previously skipped word (Rayner, 2009).

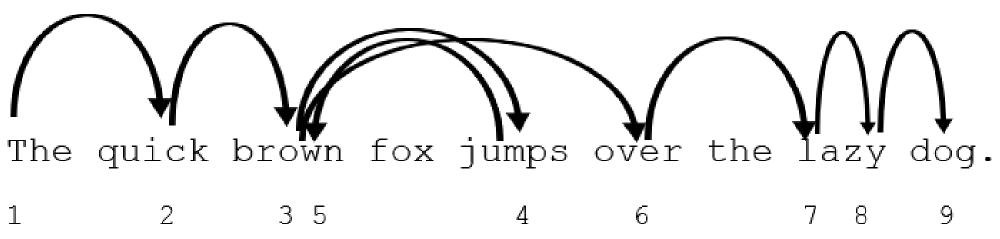

Figure 1.2. An example eye movement record show fixations (numbers) and direction of saccades (arrows), including both progressive (1, 2, 3, 4, 6, 7, 8 & 9) and regressive saccades (5), word skipping (4 & 7) and a refixation (8).

This pattern of eye movement behaviour is a consequence of limitations in retinal acuity, which is greatest within a 2° region of central vision (the *fovea)* and declines sharply with increasing distance from this point (the *parafovea* and beyond, the *periphery*). Parafoveal vision extends around 5° to the left and to the right of fixation, and in this region, visual acuity is reduced, but some useful visual information can still be obtained (Rayner, 1998). Everything beyond this is the periphery, and detailed visual information cannot be extracted from this region. Letter features can be fully resolved only within a very narrow region of around 8 letters under normal reading conditions (Rayner, 2009). This narrow region of high acuity occurs due to the distribution of different photoreceptor types across the retina. The retina is composed of two types of photoreceptors, *rods,* and *cones*. These two types of receptor serve distinct functions. Cones permit the discrimination of fine detail, while rods are specialised to detect movement and brightness. The density of cones is greatest in foveal vision, with the density of cones decreasing and rods increasing with greater distance from this point (demonstrated in Figure 1.3). Therefore, saccadic eye movements are needed to re-position the high acuity area of the retina and bring new words into foveal vision so that detailed inspection can be carried out.

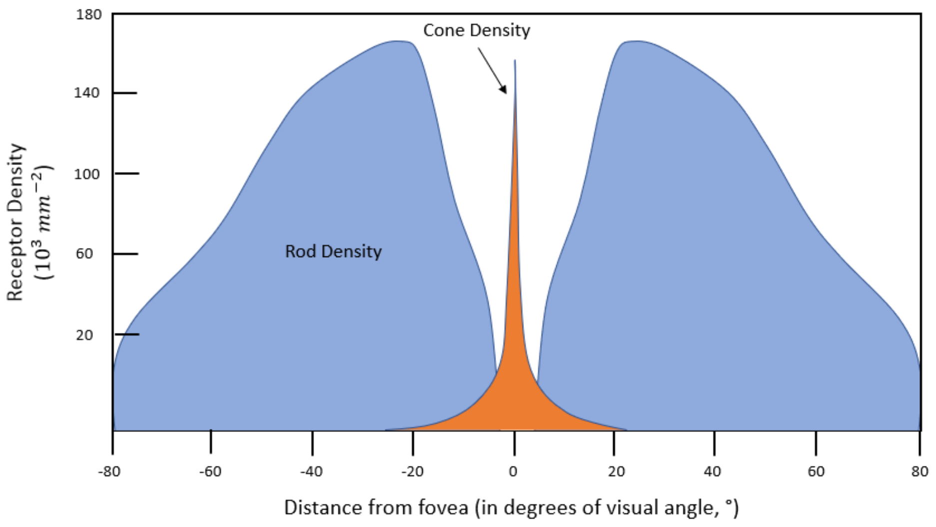

Figure 1.3. Distribution of rods and cones across the visual field. Based on data from Wandell (1995).

By using eye-tracking methods to examine eye movement behaviour we can gain greater understanding of the reading process (see Liversedge & Findlay, 2000; Rayner, 2009). Eye-tracking provides a detailed record of the reading process: where the reader looks, when they look and how long for. It has long been understood that when and where the eyes move is reflective of the mechanisms underlying reading (Landolt, 1891, cited in Huey, 1908). Studies have demonstrated direct cognitive control of eye movement behaviour during reading (Rayner, Liversedge, White, & Vergilino-Perez, 2003; Reingold, Reichle, Glaholt, & Sheridan, 2012) and factors such as reading skill and text difficulty can both influence, among other things; reading speed, fixation durations, the number of skips made and the rate of regressions (Clifton & Staub, 2011; Rayner, 1998).

1.3.2 Basic eye movement characteristics in older adults

Recent research has started to consider how eye movement behaviour during reading may differ in older age. Table 1.1 summarises studies that have investigated these issues. While many areas of older adults' processing during reading remains unexplored/underexplored, a general picture of older adults' eye movement behaviour has emerged. Compared to young adults (aged 18-30 years), healthy older adults (aged 65+) typically experience greater reading difficulty and so read more slowly despite normal levels of comprehension (Kemper & McDowd, 2006; Rayner et al. 2006; Stine-Morrow, Loveless, & Soederberg, 1996).

Manipulation/variable examined	**Relevant studies**
Control of binocular fixations	Paterson, McGowan & Jordan (2013c)
Parafoveal processing/ the perceptual span	Rayner, Castelhano, & Yang (2009); Rayner, Castelhano, & Yang (2010); Rayner, Yang, Schuett, & Slattery (2014); Risse & Kliegl (2011); Whitford & Titone (2016)
Text spacing	McGowan, White, & Paterson (2015); McGowan, White, Jordan, & Paterson (2014); Rayner, Yang, Schuett, & Slattery (2013)
Word length	Kliegl, Grabner, Rolfs & Engbert (2004)
Spatial frequency filtering	Jordan, McGowan, & Paterson (2014); Paterson, McGowan & Jordan (2013a); Paterson, McGowan & Jordan (2013b)
Time course of visual processing	Liu, Pan, Tong, & Liu (2017); Rayner, Yang, Castelhano, & Liversedge (2011)
Visual complexity	Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)
Font difficulty	Rayner, Reichle, Stroud, Williams, & Pollatsek (2006)
Word frequency	Kliegl, Grabner, Rolfs & Engbert (2004); Rayner, Reichle, Stroud, Williams, & Pollatsek (2006); Whitford & Titone (2017); Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)
Word predictability/sentence context	Choi, Lowder, Ferreira, Swaab, & Henderson (2017); Kliegl, Grabner, Rolfs & Engbert (2004); Rayner, Reichle, Stroud, Williams, & Pollatsek (2006); Whitford & Titone (2017)
Reading with distraction	Kember & McDowd (2006); Kemper, McDowd, Metcalf, & Liu (2008)
Syntactic complexity/ambiguity	Kemper, Crow, & Kemtes (2004); Kemper & Liu (2007); Stine-Morrow, Shake, Miles, Lee, Gao, & McConkie (2010)
Lexical complexity/ambiguity	Shake & Stine-Morrow (2011); Stites, Federmeier, & Stine-Morrow (2013)
Wrap-up effects	Payne & Stine-Morrow (2012)
Chinese reading	Liu, Pan, Tong, & Liu (2017); Wang, Li, Li, Xie, Chang, Paterson, White, & McGowan (in press); Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)

Table 1.1. A summary of studies to date examining eye movement behaviour during reading in older adults. Studies are categorised by the key manipulations examined. Each study may fall into more than one category. This is not an exhaustive list of all manipulations included in each study (e.g. several other studies have manipulated word frequency).

Notably, older readers show a pattern of eye movement behaviour which includes more and longer fixations and more regressive eye movements. In addition, older adults often make longer forward eye movements due to a greater likelihood of skipping past words without fixating them (e.g. Kliegl et al., 2004; McGowan et al., 2014; McGowan et al., 2015; Rayner et al., 2006). This pattern of eye movement behaviour differs markedly from other groups of slower readers, such as developing readers (see Schroeder, Hyönä & Liversedge, 2015 for a recent comparison). This has led some researchers to argue that these differences in reading behaviour reflect the adoption of a "risky" strategy, whereby older readers compensate for a slowdown in processing by inferring the identities of upcoming words based on partial word information and sentence context (Rayner et al., 2006). This results in longer forward saccades, but also more frequent regressions when these guesses prove incorrect. It is important to note that this characterisation of older adults reading behaviour is currently a matter of debate and not all studies have observed this pattern (e.g. Choi, Lowder, Ferreira, Swaab, Henderson, 2017). Further, this strategy may not be universal across all languages. Recent research with Chinese older adults shows a very different pattern of age-related differences in reading, with these readers adopting a particularly cautious strategy and skipping words infrequently (Wang et al., 2016; Zang et al., 2016). Examining eye movement behaviour across a range of orthographies will be particularly important for understanding the nature of adult age differences in reading (See Chapter 6, Section 6.3.1).

Importantly, it has not been suggested that older adults are deliberately adopting a risky strategy, but rather that this change may happen unconsciously in order to optimise performance despite cognitive and/or physiological limitations (Rayner et al., 2006). Older adults have greater reading experience than their younger counterparts and often show an advantage in vocabulary skill (Brysbaert et al., 2016) which may aid their use of this strategy. This notion of a trade-off between intact and impaired abilities can also be seen in other domains. During a test of typing speed, Salthouse (1984) found older adults showed greater impairment relative to young adults when the number of visible letters in the upcoming text was limited, suggesting they look further ahead in the text in an attempt to compensate for reduced cognitive and motor speed. This issue of whether older adults are indeed "risky" readers will be a key consideration throughout this thesis, particularly with regard to how word characteristics may modulate risky reading behaviour (e.g. by altering the rate of skipping). Chapter 3 considers this issue across the adult lifespan, including a group of middle-aged readers (risky reading is discussed further in Chapter 6, Section 6.2.4).

1.3.3 Eye-tracking technology

Eye movement recording involves monitoring eye movements as the participant reads text (in the current experiments, single sentences) presented on a computer screen. This is achieved through the use of specialised computer systems and camera equipment. The SR Research EyeLink 1000 used in the current experiments, monitors participants' eye movements by using an infrared light to illuminate the pupil causing it to generate a corneal reflection. This corneal reflection is reflected back towards the camera, which records this, and uses it to calculate a vector between the corneal reflection and the centre of the pupil (for further details, see Hansen & Ji, 2010). This is carried out while the participant fixates set locations (during calibration), and an algorithm is then used to extrapolate eye positions across the whole display. In the current experiments, calibration (and regular validation) ensured spatial accuracy <.35° of visual angle, while each letter subtended approximately .30°. Reading studies often monitor only the right eye during binocular reading tasks. Although a small disparity in the location of the two eyes is quite common, there is no age difference in this effect (Paterson et al., 2013c). A sampling rate of 1000Hz (i.e. once every millisecond) is ideal to capture fine grained details of eye movements.

1.3.4 Eye movement measures

There are a variety of eye movement measures that can be calculated. Firstly, researchers can examine measures that incorporate all fixations across a sentence. These are known as global measures, or *sentence-level measures,* and they give an indication of overall processing difficulty. Therefore, these measures are useful for examining overall differences in the reading behaviour of young and older adults e.g. for examining whether older adults read more slowly than young adults. Sentence-level analyses are reported for all experimental studies in this thesis (defined in Table 1.2).

Measure	**Definition**
Sentence reading time	The total time spent reading a sentence, from the time the text appears until a button press indicates that reading is complete and the sentence disappears.
First-pass reading time	The summed duration of fixations on a sentence that occurred the first time a word was encountered.
Rereading time	The sum of rereading fixations on a sentence within one sentence (e.g. fixations made on the second or later pass).
Average fixation duration	The mean duration of all fixations on a sentence.
Number of fixations	The total number of fixations made on a sentence.
Progressive saccade length	The average length, in characters, of each saccade made in the forward direction on a sentence in one trial.
Number of progressive saccades	The total number of saccades made in the rightward direction on a sentence.
Number of regressive saccades	The total number of leftward saccades made on a sentence which move backwards in the text (including backwards eye movements within one word).
Number of first-pass skips	The number of words in a sentence that do not receive a first-pass fixation, regardless of whether the word subsequently receives a fixation on a later pass.

Table 1.2. Sentence-level measures of eye movement behaviour reported in this thesis. All durations are measured in milliseconds.

Additionally, if a study contains a manipulation of a single word, such as a word frequency manipulation (See Section 1.4.2, a manipulation of word frequency is included in Experiment 2 and Experiment 3 (Chapter 3) word frequency is also important in Experiment 6 and Experiment 7 (Chapter 5)), or if a subset of words within a sentence are of key interest, then local analyses taking into account just fixations within a key or “critical” region can be examined. These are known as *local* analyses and are employed in Chapter 3 and Chapter 5 and are noted in Chapter 4 (these measures are defined in Table 1.3). In eye movement analyses, the currently fixated word is known as “n”, and other words can be examined with reference to their position relative to the currently fixated word (e.g. the word immediately to the left of fixation, n-1, or the word immediately to the right of fixation n+1).

Measure	Definition
First-fixation duration	The duration of the first fixation on a critical word during first-pass reading, regardless of how many fixations the word receives in total.
Single-fixation duration	The duration of the first fixation on a word, when only one fixation was made.
Gaze duration	The sum of all fixation durations on the critical word during first-pass reading prior to the reader leaving the word.
Refixation probability	The proportion of critical words that receive a second first-pass fixation.
Proportion of words skipped	The proportion of critical words that do not receive a first-pass fixation, regarding of whether this word receives a rereading fixation.
Total reading time	The sum of all time spent on the critical word, both on first-pass and subsequent passes.
Rereading time	The total time spent reading the critical word, minus the duration of the gaze duration.
Regressions in and regressions out	The proportion of critical words/ that are regressed in to or out of.

Table 1.3. Local measures of eye movement behaviour reported in this thesis. All durations are measured in milliseconds.

To examine when during the time course of processing a manipulation is having an effect, eye movement measures can be divided in to those that typically reflect early processing and those that reflect later processing. The terms “early” and “late” are often not used in a precise sense (and indeed the conception of what constitutes “early” and “late” can vary depending on the process being examined and the methods employed) and they do not map directly on to the stages of processing proposed in models of word recognition or eye movement control during reading (see Section 1.3.5). However, careful examination of when effects appear may shed light on the underlying processes (Clifton, Staub & Rayner, 2006). For example, for global measures of processing, one common way of dividing these fixations is to separate reading into first-pass and rereading (as defined in Section 1.2.1). If effects are found during first-pass reading in one condition relative to another, this usually indicates that the manipulation is acting immediately on processing the text. If an effect is observed for rereading measures, but not for earlier measures such as first-pass reading time, this is taken as an indication of the manipulation having a relatively late effect on processing (Liversedge, Paterson, & Pickering, 1998). Similarly, for local measures first-fixation duration, single-fixation duration and word skipping are generally considered to reflect early processing, while the regressions and the total reading time reflect later processing. The focus of the current thesis is on early word processing, although both early and late eye movement measures will be calculated for all experiments, as examining this full range of eye movement behaviour allows for a thorough examination of the eye movement differences between young and older adults (discussed in detail in Section 1.3.2).

Analyses

An important consideration is how best to analyse eye-tracking data. In Chapters 3, 4 and 5, data analyses were performed using linear mixed-effects models (LMEM; Baayen, Davidson, & Bates, 2008) in the statistical software R (R Core Team, 2015). LMEMs have several advantages over traditional ANOVA models. Firstly, they provide greater statistical power as they use all data rather than aggregating across data. Secondly, different sources of random error can be entered in the same model. In ANOVA, analyses for data across participants (*F*1) and across items (*F*2) are usually conducted separately (Clark, 1973). Finally, LMEMs are flexible in dealing with unbalanced data sets and missing data as the analysis weighs how much data a participant/item contributes. In addition to reporting individual contrasts, in Experiment 2 (Chapter 3), where age group contains three levels and Experiments 4 and 5 (Chapter 4), where text type contains four levels, ANOVA statistics are also reported for the LMEM models in order to examine overall main effects. However, due to the additional complexity of examining contrasts in LMEM for more complex designs with several conditions and many potential comparisons, traditional ANOVA may still be preferable and simpler to report. Traditional ANOVA results are reported in Chapter 2 (although the same pattern of results is achieved using LMEM).

1.3.5 Models of eye movement control in reading

Several computational models of eye movement control during reading have been developed which offer accounts of the various processes underlying where and when the eyes move during reading. These models can help test existing hypotheses, and also generate further predictions for research to investigate. Using empirical data as the basis for these models allows researchers to individually manipulate and inspect the assumptions of the models and see how well simulations accurately model eye movement behaviour.

Here, two particularly prominent models are discussed: the E-Z Reader model (Reichle & Drieghe, 2013; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Pollatsek, & Rayner, 2012; Reichle, Rayner, & Pollatsek, 1999), and the SWIFT model (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005). These models of eye movement control, generally, are not intended to provide a detailed account of the cognitive processing that goes on during reading. While some assumptions are made about how certain variables influence the speed of word recognition, they do not aim to explain how a word is identified (models focusing on how recognition occurs for single words are discussed in Section 1.4). Thus, they are primarily accounts of how the cognitive processes that underlie word recognition co-ordinate with the eye movement system and control the pattern of eye movements. Other models have been developed and are discussed in detail elsewhere (e.g. Competitive-inhibition: Yang & McConkie, 2001; EMMA: Salvucci, 2001; Glenmore: Reilly & Radach, 2003; The Reader: Just & Carpenter, 1980; SERIF: McDonald, Carpenter, & Shillcock, 2005; Strategy-tactics, O'Regan, 1990).

The E-Z reader model

The E-Z reader (Reichle et al., 1998; schematic of the E-Z reader model is shown in Figure 1.4) is a serial attention shift model. The main assumption is that attention is allocated to only one word sequentially and that the completion of lexical processing leads the eyes to move from one word to another.

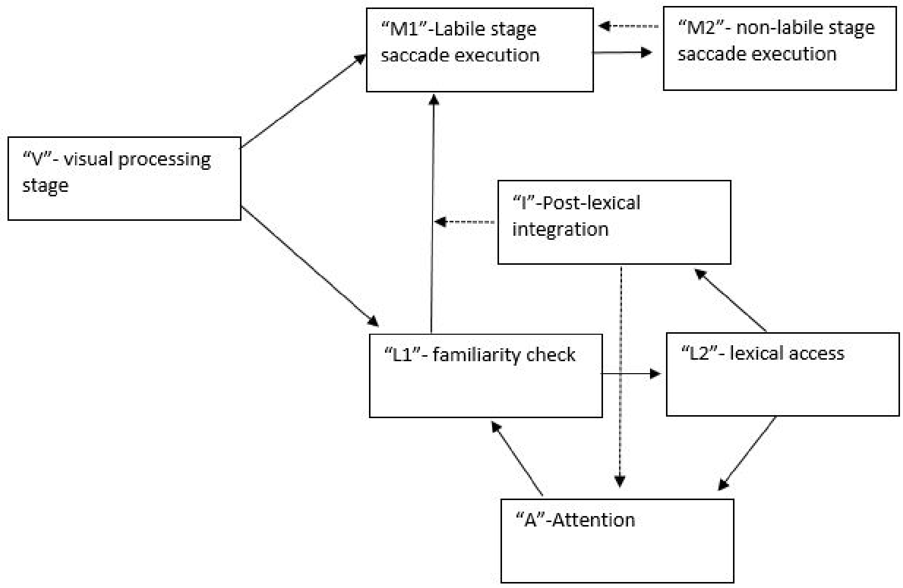

Figure 1.4. A simplified schematic of the E-Z reader model, version 10. Based on Reichle et al. (2012). The thin black arrows indicate how control is passed among components in the model, and the dashed black arrows show the transfer of control that occurs only probabilistically.

E-Z reader posits that during a pre-attentive visual processing stage, known as "V" raw visual information is extracted in parallel from across the retina. This visual information is then fed forward to the lexical processing stages. Two stages of lexical processing take place when readers fixate a word, and these two stages require focused, attentional processing. These stages are not conceptually distinct but represent different degrees of completion of the process of identifying a word. The first stage, the familiarity check, also referred to as L1, consists of initial lexical processing. Once a certain threshold is exceeded indicating that the fixated word is close enough to identification, this triggers the initiation of saccade programming to program an eye movement. Saccade programming is composed of two stages. A saccade only occurs once these two stages have completed. These stages are: a labile stage (in this stage a saccade target is identified and the distance to this target is calculated), during which a saccade can be cancelled and a non-labile stage, where the saccade can no longer be cancelled, and an eye movement will be initiated. Following L1, the second stage of lexical processing, the lexical access stage, L2, is activated. When L2 completes, this signals full lexical identification. Attention is then shifted to the next word.

The time required for L1 processing is modulated by the word's frequency, its predictability and its foveal eccentricity (i.e. the distance of the letters from central fixation, affected by both word length and fixation position). Therefore, this model can account for the typically shorter fixation times observed for words that are high-frequency, highly predictable or short in length (discussed in Section 1.4.2). E-Z reader also offers an account of why these words may be skipped. The mechanisms for attention and saccades are separate, such that attention can shift before a saccade has been executed. In this way, parafoveal lexical processing of word n+1 can begin before a saccade is made to the word. If this parafoveal processing is sufficient for the familiarly check to be completed, the saccade to this word can be cancelled (during the labile stage) and a saccade can be programmed to word n+2, resulting in word n+1 being skipped. Therefore, easier to process words e.g. predictable, high-frequency or short words are more likely to be skipped.

Recent versions of the E-Z reader model (e.g. Reichle et al., 2009; Reichle et al., 2012) also incorporate higher-level language processes in the form of a post-lexical integration stage (I). This process may intervene when meaning is not effectively processed either by keeping the reader at the location until the problem is resolved or by initiating a regression to a previous word. Reichle et al. (2009) posited two checking mechanisms, one that performs a rapid computation that something is wrong and needs immediate repair, and a second that initiates if the word cannot be integrated with the sentence context in sufficient time.

The SWIFT model

SWIFT (Engbert et al., 2005) is a parallel attention gradient model. The main assumption is that attention is distributed across several words, and therefore several words can be processed in parallel. The SWIFT model assumes that attention in reading is distributed among the currently fixated word and all words within the perceptual span (a concept discussed in Section 1.5; a schematic of the SWIFT model is shown in Figure 1.5). SWIFT posits that a word target is selected on the basis of a competition among words with different activation levels. Lexical activation for words rises during a pre-processing stage and then falls once lexical identification is complete.

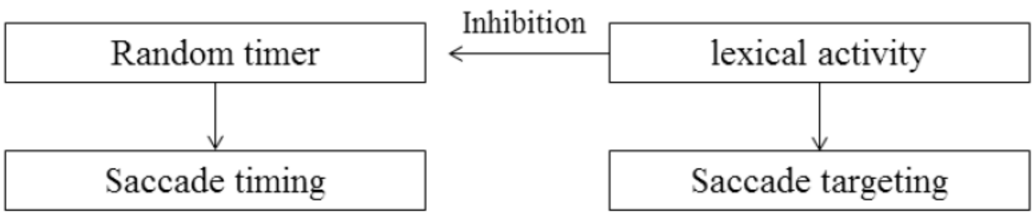

Figure 1.5. A simplified schematic of the SWIFT model. Based on Engbert et al. (2005).

SWIFT also implements separate pathways for saccade timing ("when") and saccade target selection ("where"). The decision of where to move the eyes is modulated by the relative activation of all the attended words. The word with the highest activity is the most probable target for the following saccade. The "when" decision is determined by a random timer (although this timer is modulated by lexical activation). The theoretical development of these pathways was motivated by neurophysiological findings (Findlay & Walker, 1999). In common with the E-Z reader model, SWIFT specifies two stages of saccade programming with labile and non-labile levels. During the labile stage, the oculomotor system prepares the next saccade. At this stage, a new saccade program can be initiated which leads to a cancelation of the first saccade program. At the non-labile stage, the target is selected from the field of activated words, a point-of-no-return is passed, and the saccade can no longer be cancelled.

SWIFT also specifies that fixation durations on a given word depend on its predictability, frequency and length, such that predictable, frequent and short words receive shorter fixations. Further, SWIFT posits that fixation durations depend not only on the properties of the fixated words but also on these properties of the previous (i.e., lag effects) and the next (i.e., successor effects) words. SWIFT also offers an account of word skipping. Words that have already received sufficient activation during the pre-processing stage may be skipped, even if they have not been fully identified. Skipping of word n+1 is usually preceded by a longer than average fixation on word n.

Models summary

Both of these models have been highly successful in modelling various key aspects of eye movement behaviour during reading and both models allow for the influence of variables like word frequency and word predictability on fixation times. However, there are several differences between these models. The main difference between the two models being that SWIFT proposes that processing is distributed over several words, whereas, in E-Z Reader the eye movement control system identifies each word in the sentence serially. This is still a source of ongoing debate.

Another key difference is the assumptions the models make about word skipping. With the exception of accidental skipping, E-Z reader posits that skipping occurs when recognition of n+1 is imminent whereas SWIFT assumes that skipping can occur based on incomplete parafoveal word recognition. There is currently support for both arguments (See Section 1.5.2). Throughout this thesis results will be discussed with reference to these models. Efforts to model older adults' eye movement control during reading will be discussed in Section 1.3.6.

1.3.6 Adult age differences and models of eye movement control

In order to provide a comprehensive account of eye movement control during reading, it is vital that models are able to successfully account for findings from older adults. Understanding how and why different groups of readers display different behaviour will further our overall understanding of the reading process. Recently, model developments have started to account for some age differences in processing (including changes across childhood, Reichle et al., 2013). However, to date, efforts to develop models by including data from older adults have been limited.

The E-Z reader model currently incorporates parameter adjustments to simulate some aspects of older adults' reading behaviour. Rayner et al. (2006) carried out a range of simulations based on the following general assumptions: compared with younger readers, older readers (a) have a slower rate of lexical processing and so recognise words more slowly (b) have limited visual acuity in the parafovea (c) adopt a risky reading strategy (which results in greater word misidentification) and d) show larger effects of word frequency. The parameter values for the older readers were selected through trial and error. To capture this pattern of reading behaviour four model parameters were adjusted. These adjustments were: (1) increasing the value of $\alpha_{1,}$ an intercept parameter for determining maximum mean L1 duration in order to capture a general slowdown in processing. (2) Increasing the value of α_2 to capture larger effects of word frequency on L1 duration. (3) Increasing the value of κ, a parameter that modulates the overall tendency to guess and (4) increasing the value of ε, this parameter modulates the effect that limited visual acuity has on the rate of lexical processing. More recently, McGowan and Reichle (2018) "re-confirmed" that a risky reading account is sufficient to model older adults' eye movement behaviour. Further, they found that simulations modelling solely effects of visual decline or decreased saccade accuracy were not sufficient to produce this pattern of effects.

Previous simulations were able to successfully capture the overall pattern of eye movement behaviour typically seen in older adults. However, the current thesis is especially concerned with how models might account for the role of early word recognition processes in modulating eye movement behaviour. Notably, Chapter 3 will present a stimulus quality manipulation and will examine the interplay between early visual processing and lexical processing (the above simulations suggest slower lexical processing in older adults as a result of lower visual acuity) and so the results of these experiments may have important implications for future simulations. Further Experiment 6 and Experiment 7 presented in Chapter 5 directly test the assumption made in these simulations that older adults are more likely to misidentify words.

The SWIFT model has also been adjusted to capture adult age differences in reading (Laubrock, Kliegl, & Engbert, 2006). These simulations produced a perceptual span with greater asymmetry for older adults (modelled by the parameters σ_L and σ_R, representing the left and right side of the span, respectively). However, research findings do not support this suggestion (Rayner, Castelhano, & Yang, 2009, 2010; Rayner, Yang, Schuett, & Slattery, 2014; Risse & Kliegl, 2011; Whitford & Titone, 2016). How, and if, the perceptual span changes with age remains an open question. This issue is addressed in Chapter 2. Several other modifications arising from these simulations have received greater empirical support. These include a general slowdown in lexical identification, larger effects of word frequency (discussed further in Chapter 3) and slower saccade execution.

Further research is required to more accurately and comprehensively account for older adults' eye movement behaviour. The studies in this thesis will be considered in terms of their implications for these models and may aid in their future development (discussed further in Chapter 6, Section 6.2).

1.3.7 Summary

Older adults show a range of characteristic differences in their eye movement behaviour in comparison to young adults. It is not known whether older adults differ in their early processing during word recognition compared to young adults and this is the focus of this thesis. While some work to incorporate data from older adults into models of eye movement control during reading has been undertaken, much development is still needed. The current thesis will help to address this issue by providing data on a range of early word recognition processes in older adults, which may inform future adjustments to current models of eye movement control during reading. Relevant issues in word recognition are discussed in the next section.

1.4 Word recognition during reading

This section summarises some of the key issues in understanding visual word recognition. There are numerous processes involved in word recognition and a variety of phenomena, acting at different levels of processing, that a successful model would need to explain. Here, processes (e.g. orthographic processing) and phenomena (e.g. the word frequency effect) relevant to the early stages of word recognition will be outlined. Section 1.4.1 summarises the key component processes involved in visual word recognition and outlines the methods used in the current thesis. Section 1.4.2 describes some key issues/effects relevant to the current thesis. Section 1.4.3 discusses models of word recognition and explanations for some key phenomena. Section 1.4.4 briefly considers the relationship between models of eye movement control during reading and models of isolated word recognition. Section 1.4.5 discusses issues in word recognition with reference to older adults. Section 1.4.6 summarises section 1.4.

1.4.1 Processes and methods in visual word recognition

There are several key component processes that contribute to word recognition. Theories regarding how these stages are organised and how they interact varies according to the specific model, for example, there is debate as to whether words are perceived in a feedforward manner on the basis of orthographic information, with other representations such as phonology and semantics being activated subsequently, or whether higher-order linguistic representations modulate early word recognition (see Carreiras, Armstrong, Perea & Frost, 2014). However, this section focuses only on identifying those stages.

Upon fixating a word, an elementary analysis of its visual features is carried out e.g. its length and its overall shape. This process may be made more difficult when the text is visually degraded in some way (e.g. White & Staub, 2012). Chapter 3 explores the impact of degrading text through contrast reduction for young and older adults. The orthographic features of a word are subsequently processed. Orthographic processing involves the computation of letter identity and letter position (Grainger & van Heuven, 2003). This processing is hypothesised to be performed by a set of letter detectors termed the "alphabetic array". This process is likely developed through exposure to print, and its specific organisation may depend on the characteristics of the language of exposure (e.g., McCandliss et al. 2003; Tydgat and Grainger, 2009). Whether the process of letter position coding changes with age remains to be determined and will be assessed in Chapter 4.

For young adults, at least, there is considerable evidence of the importance of contextual information, and so words that are predictable from their context are more likely to be skipped and have shorter reading times than words that are unpredictable (e.g. Balota, Pollatsek, & Rayner, 1985; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Fitzsimmons & Drieghe, 2013; Rayner et al., 2006; Rayner, Slattery, Drieghe, & Liversedge, 2011; Rayner & Well, 1996; Schotter, Lee, Reiderman, & Rayner, 2015; White, Rayner, & Liversedge, 2005). Other factors, such as a word's phonology, (McCutchen & Perfetti, 1982; Zhang & Perfetti, 1993) and its morphological structure also play an important role in word recognition (Stanners, Neiser, Hernon, & Hall, 1979). For a review of the factors known to influence the time taken to process a word, see Hyönä (2011).

Methods for exploring visual word recognition

The vast majority of studies investigating visual word recognition have involved the recognition of isolated words in tasks such as naming, lexical decision, and semantic categorisation. In the naming task, participants are presented with a word on a screen which they must name aloud as quickly as possible (Katz et al., 2011). In lexical decision tasks (LDT) participants are presented with a letter string and must quickly indicate whether the stimulus is a word or a nonword (e.g. Balota, Yap, Hutchison, & Cortese, 2012; Yap, Sibley, Balota, Ratcliff & Rueckl, 2015). In semantic categorisation, participants are presented with a word and must decide whether that word belongs to a certain semantic category (Taikh, Hargreaves, Yap & Pexman, 2015). These tasks have been incredibly influential and have yielded an enormous amount of information on the process of recognising words (see Yap & Balota, 2015, for a recent review). Results from these types of studies have been vital in the development of models of visual word recognition (e.g. Coltheart, Rastle, Perry, Langdon, & Zieglar, 2001; McClelland and Rumelhart, 1981, See section 1.4.3). These tasks are often combined with other experimental techniques, such as priming, in which another word (the prime) precedes the presentation of the target word (Meyer, Schvaneveldt & Ruddy, 1975). These isolated word recognition tasks have not only informed understanding of word processing in skilled young adult readers, but have also been used to examine the developmental trajectory of visual word recognition. Recent large-scale studies have examined visual word recognition across the lifespan in English (Cohen-Shikora & Balota, 2016) and German (Schröter & Schroeder, 2017) and have developed databases of well over 1000 words. Further, the number of isolated word recognition studies exploring word processing in older adults far exceeds the number of studies of eye movement behaviour exploring these issues (see section 1.4.5 and Table 1.1.) and these studies have contributed considerably to current understanding.

Methods employed in the current thesis

In the current thesis, all experimental stimuli consist of single sentences. When examining the processes involved in visual word recognition, it is important to consider both the processing of those words in isolation and within wider sentence context. Eye movement methodology permits the investigation of lexical processing as it occurs during normal reading. Further, the current thesis considers not only processing of fixated words, but also words in the parafovea, as processing may occur across more than one fixation. As a result, these studies are also ideally placed to address questions relating to differences in reading strategy (e.g. risky reading) as they are able to capture word skipping and regression behaviour. In order to gain informative data, the design of the stimuli and methods employed must be carefully considered. Depending on the experimental manipulation, various aspects of the stimuli must be controlled (e.g. word length, predictability/plausibility, discussed further in Section 1.4.2).

A further consideration is to ensure participants are engaged with the task and to check for any comprehension differences between young and older adults. Therefore, in all experiments comprehension questions are asked after a subset of sentences. These questions are particularly important in experiments where the experimental manipulation makes the words more difficult to read, in order to ensure that comprehension is maintained (e.g. the stimulus quality manipulation in Chapter 3 and the letter transposition manipulation in Chapter 4).

1.4.2 Key word recognition issues relevant to this thesis

This section summarises some key word recognition issues. These descriptions focus on findings from young adults. Word recognition in older adults is discussed in Section 1.4.5.

Visual processing- *effects of stimulus quality*

Reading times for words are longer when the visual properties of that word have been degraded in some way, for example, by reducing the text contrast (Drieghe, 2008; Glaholt, Rayner, & Reingold, 2014; Hohenstein & Kliegl, 2014; Jainta, Nikolova, & Liversedge, 2017; Liu, Li & Han, 2015; Reingold & Rayner, 2006; Sheridan & Reingold, 2013; Wang & Inhoff, 2010; White & Staub, 2012). Stimulus quality can also be reduced in a number of other ways, for example, by filtering the spatial frequency content of the text (Paterson et al., 2013ab) or displacing pixels within words (Marx, Hawelka, Schuster, & Hutzler, 2015). Reducing stimulus quality is an example of a manipulation of visual properties of the text, but there is also some evidence that such visual manipulations can affect lexical processing (e.g. Sheridan & Reingold, 2013). Examining joint effects of stimulus quality and word frequency can provide important support for the notion of interactions between stages of processing. Chapter 3 explores interactions between stimulus quality and word frequency.

Letter position coding- *effects of transposed letters*

When two letters within a word are switched to form a new, nonword (e.g. *teach* and *etach*), these are known as TL nonwords. TL nonwords are most commonly formed by swapping adjacent letters (e.g., *atricle-article*), but can be formed by swapping non-adjacent letters (e.g., *actirle-article*, Ktori, Kingma, Hannagan, Holcomb, & Grainger, 2014). Transposed letter nonwords have been heavily utilised in studies of isolated word recognition to study letter position coding processes. In paradigms such as LDT, previews of TL nonwords can provide facilitation for subsequent processing of the target (Perea, & Lupker, 2003ab; Perea & Lupker, 2004). In natural reading, the presence of TL nonwords slows processing (White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge & Rayner, 2008). Transposed letter effects have important implications for models of word encoding as they are informative about how the position of individual letters within a word are processed. Chapter 4 includes a letter transposition manipulation to examine whether older adults show flexible letter position coding and considers the results with reference to models of word encoding.

Lexical and post-lexical processing

The word frequency effect

Word frequency is a key variable in both models of word recognition (discussed below) and models of eye movement control during reading (discussed previously, in Section 1.2). Word frequency refers to the rate of written usage of a word and can be calculated in various ways e.g. by counting the rate of appearance of a given word within a corpus of text (e.g. books, newspapers; e.g. CELEX, Baayen, Piepenbrock, & Gulikers, 1995) or television subtitles (e.g. SUBTLEX-UK, Van Heuven, Manderab, Keuleers, & Brysbaert, 2015). A high-frequency word placed within a sentence typically receives shorter fixations and is more likely to be skipped than a low-frequency word (e.g. Inhoff & Rayner, 1986; Juhasz & Rayner, 2003; Kliegl et al., 2004; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner, Sereno, & Raney, 1996). Numerous studies have demonstrated frequency effects on a variety of fixation measures (see Rayner, 1998; Reichle et al., 2003 for summaries). This has been attributed to easier and faster identification of high-frequency words (example sentences in Figure 1.6).

I enjoyed the great *service* at the local Thai restaurant.

I enjoyed the great *cuisine* at the local Thai restaurant.

Figure 1.6. An example of sentences containing a high frequency (service) or low frequency (cuisine) critical word.

The word frequency effect can therefore be utilised to examine whether a particular manipulation affects lexical identification (e.g. Rayner, Liversedge, White & Vergilino-Perez, 2003). The effect of word frequency is unlikely to act at only one level of processing and instead is considered a general word recognition variable that is likely to influence processing of a word at many levels (e.g. both L1 and L2 in E-Z reader, and possibly later post-lexical effects, Reichle et al., 2009; Sheridan & Reingold, 2013).

Manipulations of word frequency are employed in Chapter 3 to examine the interplay between visual and lexical processing. Word frequency is also manipulated in Chapter 5 to examine word misperception. Word frequency is highly correlated with a number of other word features e.g. word length, age at which the word was acquired, and the orthographic familiarity of the letter sequences (Juhasz & Rayner, 2003) and so, where possible, these factors should be considered and controlled when developing stimuli containing a word frequency manipulation. Chapter 3 uses stimuli for which frequency values have previously been established by White, Drieghe, Liversedge & Staub (2018) (controlling for orthographic familiarity). In Chapter 5, frequency values were calculated using both the CELEX database and the SUBTLEX-UK database (with word length controlled). The CELEX database is a corpus of 17.9 million words from both written and spoken sources. While the SUBTLEX-UK database word frequencies are based on a corpus of 201.3 million words from 45,099 BBC broadcasts. The CELEX database is well established, however, recent research has suggested that word frequencies based on film and television subtitles are better predictors of processing times than frequencies based on written sources (Brysbaert, Keuleers, & New, 2011; Brysbaert & New, 2009; Cai & Brysbaert, 2010; Cuetos, Glez-Nosti, Barbon, & Brysbaert, 2011; Dimitropoulou, Duñabeitia, Avilés, Corral, & Carreiras, 2010;

Keuleers, Brysbaert, & New, 2010; New, Brysbaert, Veronis, & Pallier, 2007). So for completeness, frequencies in Chapter 5 were calculated using both databases, and values from both databases produced the same pattern of results.

Predictability and plausibility

As noted in the previous section, contextual information plays an important role in normal reading such that words that are predictable from their context are more likely to be skipped and have shorter reading times than words that are unpredictable (e.g. Balota et al., 1985; Drieghe et al., 2004; Fitzsimmons & Drieghe, 2013; Rayner et al., 2006; Rayner et al., 2011; Rayner & Well, 1996; Schotter et al., 2015; White et al., 2005). Therefore, it is particularly important when considering a critical word within a sentence, that the predictability of the words in each condition is controlled. In Chapter 3 all critical words are unpredictable from their context (White et al., 2018). Further, in addition to word predictability, it may also be fruitful to consider word plausibility, that is, how well the critical word "fits" within the sentence context. Plausibility has been found to influence the likelihood that a word will be misidentified as its higher frequency orthographic neighbour (Slattery, 2009; word neighbours are discussed in the next section) as readers make use of contextual information to avoid making errors. Further, the risky reading hypothesis (Rayner et al., 2006) predicts that older adults rely more on contextual information than young adults to guide their reading (see section 1.4.5). Therefore, a context manipulation is particularly useful for exploring whether older adults make more word misperception errors than young adults. In Chapter 5 critical word plausibility is manipulated to examine this question.

Neighbour effects

Recognition of a word is affected by that word's "neighbours", that is, words that differ by just one letter when letter number and order is maintained (e.g. "*branch*" and "*brunch*"). There are two key variables that can be manipulated to examine neighbour effects (a) the number of neighbours (neighbourhood size), (b) whether or not the word has a higher frequency neighbour (HFN). For a review of these two variables, see Perea and Rosa (2000). In LDT the presence of a HFN produces inhibition. These effects have also been studied in natural reading, where the presence of an HFN results in a greater likelihood of word misidentification (e.g. Slattery, 2009; discussed in

Chapter 5). Facilitatory effects of neighbourhood size have been observed for low- but not high-frequency words (Andrews, 1989). Common to many of the models of word encoding (including those discussed in the next section) is the notion that a visual word activates not only its own lexical representation but also representations of words that are orthographically “close” to it. Effects of encountering a word with a HFN in natural reading (and the role of context) for young and older adults are explored in Chapter 5.

1.4.3 Models of visual word recognition

Two particularly prominent models are discussed here. The basic features of the models will be discussed as well as some key predictions about the role of certain variables in word recognition. Importantly, these are models of isolated word recognition, and so do not make assumptions about how processing may be distributed across words and across fixations (though note, some research suggests that encoding of multiple words simultaneously is implausible; Reichle, Liversedge, Pollatsek, & Rayner, 2009).

The Interactive Activation model

McClelland and Rumelhart (1981; see also Davis & Lupker, 2006) developed the Interactive Activation Model (shown in Figure 1.7). This model was specifically intended to explain the effects of higher-level information on lower-level processing, in particular, the word superiority effect (letters within words are easier to recognise than letters presented within nonwords, Reicher, 1969; Wheeler, 1970). The central feature of this model is the assumption that processing consists of several levels corresponding to visual features, letters and words and information flows through these different levels of representation continuously. When processing begins, there is a continuous flow of activation upstream from feature-level representations to letter-level representations to word-level representations, as well as downstream from word-level representations back to lower level representations (“feedback activation”). There is also a flow of inhibition between representations at the same level. Lexical selection is achieved when the activation in a lexical representation exceeds a threshold. Upon encountering a word, the initial letter in the word will activate word nodes for all possible candidates while inhibiting all other word nodes.

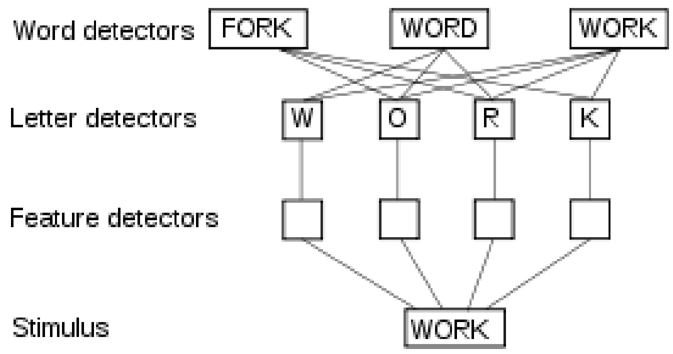

Figure 1.7. A schematic of the Interactive Activation model. From McClelland and Rumelhart (1981).

This model is able to account for several key phenomena (in addition to the word superiority effect), such as the word frequency effect. In this model the resting level activations of word-level representations are frequency dependent. Thus, once activated, representations for high-frequency words will reach their activation threshold more quickly than representations for low-frequency words. Further, the model offers predictions about how orthographic representations are coded. This model employs strict letter position encoding in which letter identity and letter position are coded at the same time. This creates difficulties in accounting for findings indicating flexible letter coding of letter position (this issue is discussed in Chapter 4).

This model also offers some explanation of neighbour effects. According to Jacobs and Grainger (1992), the intra-level inhibition between the lexical units of the model should delay the activation of a word with HFNs such that when a neighbourhood is activated by a word, each lexical unit begins to inhibit its neighbours. Higher frequency words have higher resting levels of activation and so are more powerful inhibitors, and so a word with HFNs receives more inhibition, delaying activation. However, low-frequency words with many neighbours produce facilitation in LDT compared with low-frequency words with few neighbours (Andrews, 1989, 1992). This finding has been difficult to reconcile with the notion of lexical competition. Indeed, Grainger and Jacobs (1996) simulations failed to capture this effect. To explain this apparent discrepancy, Grainger and Jacobs (1996) argued that the facilitative effect was due to task-specific factors in LDT. Effects of word neighbours in sentence reading with young and older adults are considered in Chapter 5.

This model has been extremely influential and has formed the core of a number of other models, including the Dual-route Cascaded model. However, this model does not provide a comprehensive account of word recognition, with little to say about the role of factors such as phonological processing, meaning or relevant context.

Dual-route Cascaded model

The Dual-route Cascaded model (Coltheart, Rastle, Perry, Langdon, & Zieglar, 2001) is a model of word recognition and reading aloud. It is a cascade model because activation at one level is passed on to the next before processing at the first level is complete. This model proposes two main routes to word recognition, both starting with orthographic analysis. The route used will depend on the reader's familiarity with the current word. Route 1 is the grapheme-phoneme correspondence route. This route involves converting letters into sounds. This route allows unfamiliar words to be recognised by converting individual letters to phonemes. The second route can be subdivided in to the lexical semantic route and the lexical non-semantic route. The lexical semantic route has been described a dictionary "look-up" procedure. The input word is activated in the lexicon and its meaning is obtained from the semantic system. This process is used to allow skilled readers to quickly recognise a familiar word. The lexical non-semantic route is very similar but bypasses the semantic system. Each of these routes is composed of a number of interacting layers.

1.4.4 Integrating models of visual word recognition and models of eye movement control during reading

As researchers develop a fuller understanding of the reading process, it will be important to develop accounts of lexical processing that can be realistically incorporated into models of eye movement control during reading. This could include offering an account of how lexical processing is integrated across successive fixations, including the processing of both foveal and parafoveal information. Examining issues of word recognition within natural sentence reading, such as the experiments contained within the current thesis, will be vital in achieving this. This aim of an integrated model has been the subject of discussion for several years (Rayner & Reichle, 2010), but only recently has computational modelling started working towards this. Recently, Reichle (2015) described current efforts to develop a more comprehensive description of reading by embedding word-identification, sentence-processing, and discourse representation models within the framework of E-Z Reader. This issue is discussed further in the General Discussion of this thesis (Chapter 6, Section 6.3.2).

1.4.5 Early word recognition in older adults

Some studies have provided an important initial suggestion that there may be differences in early word recognition processes between young and older adults. As the relevant findings are discussed at length in the experimental chapters, only a brief overview is provided here (see also, Table 1.1). In addition, several of the issues investigated in this thesis have not previously been investigated with reference to older adults' word recognition (effects of reduced stimulus quality, letter position coding) either in isolated word recognition tasks or in studies of eye movement behaviour during reading.

Older adults have sometimes been shown to produce larger word frequency effects than young adults, such that older adults recognise low-frequency words particularly slowly. However, the evidence for this is mixed, particularly in studies of isolated word recognition (Bowles & Poon, 1981; Tremblay & Lecours, 1989; Balota & Ferraro, 1993, 1996; Spieler & Balota, 2000). Balota, Cortese, Sergent-Marshall, Spieler, & Yap (2004) found that results may vary depending on the task used (naming tasks are more likely to produce this effect than LDT). Larger word frequency effects for older adults have also been indicated in studies of eye movements during sentence reading with older adults making disproportionately longer fixations on low-frequency words (Kliegl et al., 2004; McGowan, White & Paterson, 2015; Rayner et al., 2006; Whitford & Titone, 2017; though note that this effect is often small and has not been found consistently across all studies: McGowan et al, 2014; Rayner et al., 2013). Such results are in line with the possibility that lexical processing of words may be more difficult for older compared to younger adults. Older adults also have a tendency to show larger and more consistent effects of word frequency on word skipping rates

(Kliegl et al., 2004; Rayner et al., 2006; but see Rayner et al., 2011), suggesting that they may use this information to "guess" upcoming words.

There is also evidence from studies of isolated word recognition that older adults' responses are slowed more than young adults when the presented stimulus is degraded (Madden, 1988, 1992). However, it is not yet known how this may affect older adults' eye movement behaviour during sentence reading, nor is it known the mechanism by which this effect occurs. Chapter 3 provides an additional test of the word frequency effect in older adults, both for normally presented words and low-contrast words.

There is also some evidence from isolated word recognition tasks (Cohen & Faulkner, 1983; Madden, 1988; Speranza, Daneman, & Schneider, 2000) that older adults make greater use of contextual information to inform their reading. This suggestion is key in assessing the "risky" reading hypothesis. However, studies of eye movement behaviour during reading have failed to provide a consistent answer. Indeed, Rayner et al.'s seminal 2006 paper failed to find any age difference in the use of contextual information. More recently, Choi et al., (2017) reported larger effects of predictability for older than younger adults, but no age differences in the effects of a word's predictability on skipping rates (a key test of risky reading). Chapter 5 addresses this issue using a plausibility manipulation to uncover whether older adults make more word misperception errors when a more frequent word (a HFN) fits within the sentence context. There is also some indication from LDT that older adults do not show the standard inhibition response to words with a HFN (Robert & Mathey, 2007). This was taken to support an age-related decline in lexical inhibition and activation. However, how the presence of a HFN affects the pattern of eye movement behaviour and how this is modulated by sentence context is still unknown.

Overall, there is clear reason to consider that early word recognition processes may differ in young and older adults. However, a number of open questions remain. Many of these issues have not been explored with older adults (letter position coding, misperception of HFNs). Further, many of these issues have not been examined using eye movements during reading despite adult age differences in eye movement behaviour being well-established.

1.4.6 Summary

A variety of processes contribute to efficient word recognition. How this processing may differ for older adults is not yet understood and is not well specified in models of word recognition. Several key issues are addressed in this thesis, including effects of stimulus quality (Chapter 3), letter position coding (Chapter 4) and misperception of orthographic neighbours (Chapter 5).

1.5 Parafoveal processing in reading

During naturalistic reading, early word recognition processes begin when words are outside of central vision, in parafoveal vision. Therefore, parafoveal processing can be considered a key aspect of early word processing. Understanding how much and what types of information are processed in the parafovea is vital to understanding normal reading. This section explores the role of parafoveal processing in reading. Section 1.5.1 discusses the evidence for the role of parafoveal processing in normal reading for young adults and the paradigms used to explore parafoveal processing, Section 1.5.2 looks specifically at the evidence from word skipping, Section 1.5.3 briefly explores parafoveal processing in older adults and Section 1.5.4 provides a summary of Section 1.5.

1.5.1 Parafoveal processing in reading

There is a wealth of evidence demonstrating that in normal reading (even when words are not skipped) readers make use of parafoveal information to guide eye movements and pre-process word features before they are fixated (Rayner, 2009; Schotter, Angele, & Rayner, 2012). Further, reading is slowed by the removal of parafoveal information, and so parafoveal information must serve to inform natural reading (Rayner, Well, Pollatsek, & Bertera, 1982). This section outlines current understanding relating to parafoveal processing. First, the key methods used to explore parafoveal processing are outlined.

Gaze-contingent techniques

Eye-tracking enables the implementation of gaze-contingent techniques, where the text displayed to the reader changes in response to movements in the location of the eyes in the text. Gaze-contingent techniques are used in Chapters 2, 3 and 4 of this thesis. Some of the gaze-contingent methods employed in this thesis are well established, while others apply innovative adaptations to this technique. One such gaze-contingent method is the *moving-window* technique. In this method, the amount of normally presented text displayed to the reader is restricted. A window of normal text is available around the fixated word (McConkie & Rayner, 1975), and this window moves in synchrony with the reader's eyes, such that the window is updated every time a new fixation is made (see Figure 1.8). This restricts the availability of parafoveal information. This technique has been employed in a number of studies to investigate the perceptual span, that is, the region around fixation in which readers show sensitivity to visual information, such as orthographic (i.e., letter) information during natural reading (discussed in greater depth in Section 1.5). The basic assumption is that when the window is smaller than the perceptual span, reading will be disrupted. The size of the window can be varied in order to locate the point at which eye movement behaviour returns to normal, this window represents the size of the perceptual span. Chapter 2 explores the perceptual span in young and older adults using a gaze-contingent moving-window.

```
                  *
Xxx xxxxx xxxxx fox xxxxx xxxx xxx xxxx xxx.

                        *
Xxx xxxxx xxxxx xxx jumps xxxx xxx xxxx xxx.

                  *
Xxx xxxxx xxxxx fox xxxxx xxxx xxx xxxx xxx.
```

Figure 1.8. Example of a one-word moving-window. An asterisk (*) represents the point of fixation.

Gaze-contingent methods can also be used in other ways, for example to present manipulations only during first-pass reading, only during rereading or to present a manipulation only foveally or only parafoveally (for examples of these types of manipulations, see Marx, Hawelka, Schuster, & Hutzler, 2015; Rayner, Yang, Schuett, & Slattery, 2014; White, Lantz, & Paterson, 2017). Several studies have also employed moving-window techniques in experiments with older adult participants (e.g. Rayner, Castelhano, & Yang, 2009; Rayner et al., 2014; Whitford & Titone, 2016; See Chapter 2). Chapter 3 includes an example of using gaze-contingent technique to manipulate only upcoming text in the parafovea. Chapter 4 employs a gaze-contingent technique to limit the manipulation only to first-pass reading. The utility of such techniques will be discussed in more detail in the relevant chapters.

Research exploring parafoveal processing during reading has often employed the *boundary technique* (McConkie & Rayner, 1975) to examine the types of information that may be processed parafoveally. In this technique, an invisible boundary is placed in the text, prior to fixating a critical word the reader is provided with either a valid or an invalid preview of the target, once the eyes cross the invisible boundary the preview is replaced with the correct word (example in Figure 1.9). As this change is made during a saccade, when vision is suppressed, the reader is usually unaware that any change has taken place. The logic of this approach is that, if a reader is able to parafoveally process certain characteristics of a word (e.g. its orthography), then removing this information (by providing an invalid preview) would disrupt the processing of this word. Indeed, readers presented with a valid preview of a target show a benefit of around 30-50ms, compared to when they are presented with an invalid preview (Schotter et al., 2012), this difference is termed the *preview benefit*. This suggests that readers benefit from being able to begin processing words before they are fixated (see also, Schotter & Leinenger, 2016 for a recent re-consideration of these effects).

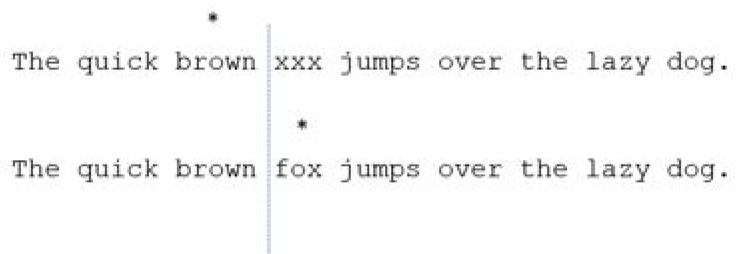

Figure 1.9. An example of a boundary change. The dashed vertical line represents the invisible boundary. Once the reader's eyes cross the boundary, the preview is replaced with the correct word.

Parafoveal processing

An important issue is exactly how much information is pre-processed during normal reading. Moving-window studies have shown that parafoveal processing of orthographic information typically extends around 14-15 letters to the right of fixation and around 3-4 characters to the left of fixation in young readers (Rayner & Bertera, 1979; Rayner et al., 1982). This processing region is known as the *perceptual span*. The perceptual span is asymmetric. However, the size and shape of the perceptual span is largely determined by attentional factors, rather than just limitations in visual acuity. The perceptual span increases as reading skill increases (Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986). The perceptual span is thought to reduce in size when text is more difficult to process (Henderson & Ferreira, 1990) and is smaller in logographic languages, such as Chinese, where characters have greater visual complexity (Inhoff & Liu, 1998; Shen, Bai, Yan & Liversedge, 2009). The asymmetry of the perceptual span is also dependent on reading direction and the span is asymmetric in a leftward direction for languages which are read from right to left, such as Hebrew (Pollatsek, Bolozky, Well, & Rayner, 1981). However, span size remains consistent when letters in the parafovea are magnified to offset acuity limitations (Miellet, O'Donnell, and Sereno, 2009).

Research utilising the boundary technique has established that low-level visual features, such as word length, can be extracted parafoveally. Inhoff, Starr, Liu and Wang (1998) demonstrated that previews of the correct word length speed up processing compared to previews of incorrect length. Much research has demonstrated that orthographic information can also be processed prior to fixation (see Rayner, 1998 for a review; and Experiment 1, Chapter 2). Research using homophones has also provided consistent evidence that phonological information can be processed parafoveally (e.g. Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris & Rayner, 1992). However, readers do not appear to extract information about a word’s morphology parafoveally (e.g. Kambe, 2004; but there is evidence that readers of Hebrew process extract morphological information in the parafovea, see Deutsch, Frost, Pelleg, Pollatsek & Rayner, 2003; Deutsch, Frost, Pollatsek & Rayner, 2005). Early investigations in English suggested that semantic information cannot be obtained parafoveally (Rayner, Balota & Pollatsek, 1986). However, more recently Schotter and

Jia (2016) found that under certain circumstances, information about a words semantic plausibility can be processed parafoveally. Further, there is evidence for a semantic preview benefit in both German and Chinese (Hohenstein & Kleigl, 2014; Hohenstein, Laubrock & Kliegl, 2010; Yan, Richter, Shu & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2015; Yang, Wang, Tong, & Rayner, 2012).

1.5.2 Word skipping

During normal reading, up to 30% of words are skipped (Rayner, 1998). The extent to which words that are skipped are processed in the parafovea is a matter of some debate. Certainly, lexical and semantic characteristics of a parafoveal word influence the likelihood that a word will be skipped; frequent words are skipped more often than infrequent words and predictable words are skipped more often than unpredictable words (for a review of these studies, see Brysbaert, Drieghe & Vitu, 2005; Schotter, Angele, & Rayner, 2012), suggesting that these features are being processed parafoveally. However, Binder, Pollatsek and Rayner (1999) found that the effects of inaccurate post-views are stronger when the word was initially skipped and this could be attributable to words being skipped prior to their full lexical identification. Views on this vary dramatically, on the one hand it has been claimed that the decision to skip is essentially an educated guess based on coarse-scale information (e.g. Brysbaert & Vitu, 1998). On the other, it has also been claimed that a word is usually skipped because it will be identified imminently (i.e. the L1 stage of lexical identification has completed, e.g. Reichle et al, 2003) and that information from all letters can be used to inform skipping (Drieghe, Rayner, & Pollatsek, 2005). Ultimately, uncovering the nature of word skipping will have important implications for models of eye movement control during reading.

1.5.3 Parafoveal processing in older adults

The loss of visual abilities associated with older age (discussed in detail in section 1.2) are generally greater outside of central vision (in the parafovea), such as increases in the effects of crowding (Scialfa et al, 2013). Therefore, it is reasonable to hypothesise that parafoveal processing may differ in older adults. It is not yet known whether these reduced visual abilities impair older adults' parafoveal processing of upcoming words. There is currently some evidence that older adults are less efficient than young adults in processing non-foveal information during non-reading tasks (Ball, Beard, Roenker, Miller, & Griggs, 1988; Sekuler & Ball, 1986). However, whether these changes impact on parafoveal processing during reading has yet to be established. To date, a few studies have looked at this issue (e.g. by examining the perceptual span: Rayner, Castelhano, & Yang, 2009; Whitford & Titone, 2016) however results have not been consistent. Chapter 2 focuses on addressing this gap in the literature by examining the perceptual span in young and older adults. Further, examining the skipping behaviour of older adults has the potential to provide important insight into the processes that drive word skipping, as a key assumption of the risky reading hypothesis (Rayner et al., 2006, see Section 1.3.2) is that older adults are skipping words on the basis of only partial word information. There is already some evidence that older adults show larger and more consistent effects of word frequency on word skipping rates (Kliegl et al., 2004; Rayner et al., 2006; but see Rayner et al., 2011). Word skipping will be examined in experiments throughout this thesis.

1.5.4 Summary

Parafoveal processing is important for normal skilled reading. There is substantial evidence that low level visual features, orthographic and phonological features can all be processed parafoveally. There is also some evidence that semantic information can be processed parafoveally. There is also reason to believe that parafoveal processing may be impaired in older adults and this will be explored in Experiment 1 (Chapter 2). Also, the role of parafoveal preview in driving effects of stimulus quality and word frequency is examined in Chapter 3.

1.6 Summary and overview of thesis

Chapter 1 has outlined a range of issues in understanding the processes that underlie efficient word recognition during natural reading. This chapter has also highlighted the importance of understanding adult age differences in reading and demonstrated clear gaps in current understanding. There are a range of processes that contribute to word recognition. This thesis will focus on an examination of early processes in word recognition, especially, parafoveal processing, visual processing and lexical processing. The seven experiments presented in this thesis have been carefully designed to provide a thorough examination of these issues. This thesis will extend current knowledge regarding the nature of adult age differences in reading and will have important implications for models of eye movement control during reading and models of isolated word recognition.

Accordingly, this thesis contains seven experiments addressing important questions regarding older adults' early word processing. *Chapter 2* presents Experiment 1 which examines whether older adults display impaired parafoveal processing and so have a smaller perceptual span than young adults, addressing the open question highlighted in Section 1.5.3. *Chapter 3* presents Experiment 2 and Experiment 3 which examine whether older adults experience greater reading difficulty resulting from poor stimulus quality (in this case, low contrast text, discussed in Section 1.4.2) than young adults and examines the interplay between the processing of early visual features and lexical processing. These issues have not previously been explored using eye-tracking with older adults. *Chapter 4* examines the coding of letter position information in young and older adults, providing a novel test of how well current accounts of letter position coding capture these processes for older adults (discussed in Section 1.4.3). These issues have not previously been explored. *Chapter 5* explores the notion that older adults are more likely to misperceive words than young adults, providing a novel and important test of the "risky" reading strategy outlined in Section 1.3.2. Finally, *Chapter 6* discusses the implications of these findings and suggests some directions for future research.

Chapter 2:

Adult age differences in the perceptual span

The extent to which parafoveal processing of text differs in older age is uncertain. Some research has indicated that compared to young adults, older adults have a smaller perceptual span and so acquire linguistic information from a narrower and more symmetric region on each fixation. This age difference in parafoveal processing could be an important component of the greater reading difficulty older adults typically experience. However, recent research has failed to replicate this finding and so this remains an open question. Accordingly, to investigate this issue, Experiment 1 used a gaze-contingent moving-window technique to assess the parafoveal processing of orthographic information by young (18-25 years) and older (65+ years) adult readers. This involved substituting letters in words at locations to the right and left of fixation and examining the effects of these changes on eye movement behaviour. Critically, this experiment employed an improved methodology using visually similar letter masks which preserved word shape. The findings showed parafoveal processing effects consistent with previous reports for young adults with both young and older adults showing an asymmetric span. However, interactions between age and window condition indicate that removing parafoveal orthographic information affects the reading of young and older adults differently. Crucially, in contrast to previous studies, no substantial age differences in the size of the perceptual span were observed. Overall, these results demonstrate that adult age differences in the perceptual span are not an important component of age-related reading difficulty.

2.1 Introduction

Experiment 1 examines differences in the perceptual span of young and older adult readers. For young adults, there is substantial evidence that the parafoveal processing of text is a crucial component of skilled reading (see Schotter, Angele, & Rayner, 2012 for a review, parafoveal processing in normal reading is discussed in Chapter 1, section 1.5.1). Indeed, a marked slowing of reading speed has been observed when only the fixated word is available to the reader (Rayner, Well, Pollatsek, & Bertera, 1982). In particular, orthographic information is used to pre-process letter identities within upcoming words to facilitate subsequent foveal processing and guide decisions about where to move the eyes (e.g. Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; McConkie & Rayner, 1975; Rayner, 1975; Rayner et al., 1982; White, Johnson, Liversedge, & Rayner, 2008). Further, research has also highlighted the importance of parafoveal processing to the left of fixation to guide regressive eye movements and perhaps to continue processing words skipped prior to full identification (Apel, Henderson, & Ferreira, 2012; Binder, Pollatsek, & Rayner, 1999; Veldre & Andrews, 2014).

Many of the visual difficulties associated with older age are greater outside of central vision (Crassini, Brown, & Bowman, 1988; Owsley, 2011) and become more pronounced with increasing eccentricity, e.g. adult age differences in the effects of crowding (outlined in Chapter 1, Section 1.2.1) (Scialfa, Cordazzo, Bubric, & Lyon, 2013). Given this, an important question concerns whether reduced visual abilities impair older adults' parafoveal processing of upcoming words. As the aim of the current thesis is to examine differences in early word recognition processes between young and older adults, a natural starting point is to examine the processing that takes place even before a word is fixated. Therefore, Experiment 1 provides an important test of parafoveal processing in young and older readers. The following sections summarise current evidence from both non-reading studies of parafoveal processing and reading studies of parafoveal processing in older adults.

Non-reading studies of parafoveal processing in older adults

An initial indication that older adults may be less able to make effective use of non-foveal information than young adults comes from non-reading tasks examining the *useful field of view*. The useful field of view is defined as the visual area within which information can be acquired in one eye fixation. In visual search tasks, it has been found that older adults display particular difficulties in identifying peripheral targets in the presence of distracters and that the area from which target information can effectively be extracted is smaller in comparison to young adults, indicating a smaller useful field of view (Ball, Beard, Roenker, Miller, & Griggs, 1988; Sekuler & Ball, 1986). Additionally, these studies observed that the size of the field seems to reduce as a function of age. Similarly, Edwards et al. (2006) found that while many factors contributed to the size of the useful field of view, such as visual ability and education, age accounted for the most variance. These studies suggest that processing outside of foveal vision may be less efficient in older adults, however, importantly it is not yet known whether these difficulties translate in to reduced parafoveal processing during reading.

Reading studies of parafoveal processing in older adults

Some more recent studies employing eye-tracking methods during reading tasks have also pointed towards impaired parafoveal processing in older adults. Rayner, Yang, Schuett and Slattery (2014) used foveal and parafoveal masks to investigate processing of parafoveal information by young and older readers. In this study, using a *gaze-contingent moving-window* (detailed in Chapter 1; Section 1.5.1), the foveal word was masked by “x”s as soon as it was fixated. This study found that masking the foveal word during reading was more detrimental to the reading speed of older adults than young adults, with older adults experiencing reading speeds three times longer than in normal reading, compared to reading speeds one-third longer than those seen in normal reading for young adults. This finding was interpreted as suggesting that older adults rely more on the foveal word as they are less able to make use of the information presented parafoveally.

Further indication of impaired use of parafoveal information by older adult readers comes a study investigating the perceptual span (defined in Chapter 1, Section

1.5.3). The gaze-contingent moving-window technique has been particularly important in the study of the perceptual span. This paradigm has been used extensively to examine the perceptual span in young adult readers. Studies utilizing this technique effectively established the presence of an asymmetry in young adults' perceptual span (McConkie & Rayner, 1976; Underwood & McConkie, 1985). More recently this method has been employed as a means of comparing the size of the perceptual span for young and older adults. Rayner, Castelhano and Yang (2009) found that young adults gained greater benefit from having parafoveal orthographic information to the right of fixation (i.e. a greater reduction in reading speed, compared to having no information available to the right of fixation) than older adults, while older readers gained greater benefit from the availability of information to the left of fixation (i.e. a greater reduction in reading speed, compared to having no information available to the left of fixation) compared to young adults. From this, the researchers posited that older adults process less information to the right of fixation when reading, but process information to the left of fixation to a greater extent than young adults, resulting in a more symmetric perceptual span. Using a different gaze-contingent method, the boundary paradigm (defined in Chapter 1, Section 1.5.1), Rayner, Castelhano and Yang (2010) found that older adults obtained less preview benefit for word n+1 than young adults, again indicating that older adults make less use of information to the right of the fixated word than young adults during reading.

The above studies support the idea of a smaller, more symmetric span for older readers. However, research in this area is inconsistent and recent studies have failed to observe these size and symmetry differences. Risse and Kliegl (2011) using the boundary paradigm found that both young adults and older adults gained significant preview benefit from both word n+1 and n+2, suggesting that both age groups are sensitive to information two words to the right of fixation. Interestingly, in this study, word n+1 was always very short (three letters long), so processing difficulty was manipulated (discussed further in Section 2.3). However, the same measures to manipulate processing difficulty were not taken by Rayner et al. (2010), who used n+1 words of a range of lengths. These discrepancies in methodology may go some way to explaining the different results seen in various studies and indicate that further research is still needed. Payne and Stine-Morrow (2012) also found intact preview benefit for word n+1 in older adults (although older adults experienced greater disruption due to sentence wrap-up effects than young adults, see Section 2.3). Additionally, as well as foveal masks, Rayner et al. (2014) also created conditions that masked parafoveal information either to the left or to the right of fixation during reading. Few age differences in the response to these left and right masks were observed. While this study is not able to indicate the size of the perceptual span for older adults, it suggests that they may rely on information to the left and right of fixation to a similar degree to young adults. Finally, Whitford and Titone (2016) used a moving-window paradigm to assess age differences in the perceptual span of bilingual readers and found no age difference in the perceptual span during either first- or second-language reading (for further evidence that parafoveal processing is no less efficient in older age, see Schroeder, Eilers & Tiffin-Richards, 2018). Therefore, the extent to which young and older adults differ in the parafoveal processing of text remains unclear and recent research indicates that differences between young and older adults in parafoveal processing may not be as apparent as once assumed.

A particular concern for the present research was that moving-window paradigms in which letters in words outside of a window are replaced by an “x” may not provide a particularly effective method for investigating age differences in parafoveal processing. This type of text replacement creates a uniform and highly salient pattern in peripheral vision that is distinct from normal text and so may interfere with normal reading. Moreover, this interference may be greater for older than younger adult readers as older adults typically have greater difficulty ignoring distracting visual information (Chapter 1, Section 1.2.1; Kemper & McDowd, 2006; Mund, Bell, & Buchner, 2010). Therefore, studies that use this technique may not provide an accurate indication of adult age differences in performance (and for further discussion of limitations of using “x” -masks, see Gagl, Hawelka, Richlan, Schuster, & Hutzler, 2014; Paterson, McGowan, & Jordan, 2013).

Similar concerns may also apply to the study by Whitford and Titone (2016). In particular, while this study showed no age differences in span size, it used a masking technique in which both letters in words and spaces between words outside the moving window were replaced by a dash (-). As with “x”-masks, this technique produces a uniform pattern outside of each window that may interfere with normal reading, but the dashes may also provide a less salient cue to the letter locations (as a dash contains fewer pixels). Crucially, the dashes also removed spatial cues to the length and location of words. Consequently, both young and older adults may have had difficulty targeting saccades towards upcoming words when these spatial cues were lacking, and this may have contributed to the absence of an age difference in perceptual span effects in this study.

Studies to date have employed different techniques and mask types and have produced inconsistent results (these studies are summarised in Table 2.1). It is clear that further research is needed to understand the effects of ageing on parafoveal processing. Particularly, research is required which makes use of the moving-window paradigm as this allows for an assessment of exactly how much information either side of fixation is required for normal reading, and therefore can provide an indication of the size and symmetry of the perceptual span in older adults. Experiment 1 replaces letters within words with visually similar letters, therefore, this study examines detailed orthographic processing in the parafovea, beyond the level of word shape.

Authors	Technique	Mask Type	Age differences in parafoveal processing?
Rayner, Castelhano, & Yang (2009)	Moving-window	Parafoveal x-mask	**Yes-** older adults' perceptual span smaller and more symmetric.
Rayner, Yang, Schuett, & Slattery (2014)		Foveal or parafoveal x-mask	**Yes-** greater increase in reading times for older adults when foveal word masked.
Whitford & Titone (2016)		Parafoveal dashes (-)	**No-**perceptual span extending roughly 14 characters to right of fixation for age both groups.
Experiment 1		Visually similar letters	**No-**perceptual span extending roughly 2 words to the right and 1 word to the left of fixation for both age groups.
Rayner, Castelhano, & Yang (2010)	Boundary change	Visually similar letter string preview	**Yes-** preview benefit attenuated for older adults.
Risse & Kliegl (2011)		Visually similar letter string preview	**No-** n+1 and n+2 preview benefit for both age groups.
Payne & Stine-Morrow (2012)		Visually dissimilar letter string preview	**No-** similar n+1 processing for both age groups.

Table 2.1. A summary of studies examining adult age differences in parafoveal processing.

2.2 Experiment 1

The previous studies examining parafoveal processing in older adults have failed to provide a clear picture. Further, the methods often used to mask parafoveal information are not ideal. Accordingly, the current study aimed to: 1) Clarify whether young and older adults differ in their parafoveal processing of orthographic information during reading. 2) Reveal whether older readers show a more symmetric perceptual span than young readers and 3) employ an improved method allowing for a detailed examination of the perceptual span.

Young and older adults read sentences presented in one of six window conditions, as shown in Figure 2.1. The conditions manipulated whether information was available in only one direction (left or right) or contained all parafoveal information in one direction plus one additional word on the other side of fixation.

If older adults do indeed have a smaller perceptual span than young adult readers, in line with Rayner et al. (2009; 2010), then age and window condition will interact such that older adults require a smaller window size in order to read normally. Young and older adults may also respond differently to the removal of parafoveal orthographic information in other ways e.g. older adults may benefit more (show greater reduction in reading speed) than young adults when information to the left of fixation is provided, indicating a more symmetric perceptual span, in line with the findings of Rayner et al. (2009). Alternatively, it could be that, in line with Risse and Kliegl (2011) and Whitford and Titone (2016), older adults show a similar perceptual span to young adults, in which case only main effects of age and main effects of window size will be observed.

2.2.1 Method

Participants. All experiments in this thesis received ethical approval from The University of Leicester Ethics committee (Psychology). Eighteen young adults (*M*= 19.56, range= 18-25 years, 12 female) participated for course credit and eighteen older adults (*M*= 68.56, range= 65-74 years, 11 female) took part in the study for a small payment. The young participants were recruited from the University of Leicester Undergraduate population and the older adults were recruited from Leicester and the surrounding communities. Participants were all native English speakers with no history of dyslexia or serious eye diseases. Participant characteristics are summarised in Table 2.2. Participants were required to have either normal or corrected-to-normal vision and wore glasses if needed. Older adults showed poorer performance than young adults on all vision tests. Participants were screened to ensure that their high contrast (corrected) acuity was at least 20/40 at the screen viewing distance (80cm). Visual acuity was assessed using the charts detailed in Chapter 1 (Section 1.2.1).

There was no significant difference in the number of years of education the two age-groups had received and all participants reported in engaging in several hours of reading activity each week (all *p*s> .05). In addition to the participants included in the analyses, four additional older adults and two young adults were replaced for reasons including poor visual acuity, tracking difficulties and poor comprehension scores (below 85%). All participants were naïve in relation to the purpose of the experiment.

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/18	20/14-20/32	20/28	20/17-20/38
Low contrast near acuity	20/25	20/20-20/50	20/46	20/26-20/66
High contrast distance acuity	20/18	20/13-20/32	20/26	20/20-20/40
Low contrast distance acuity	20/29	20/20-20/53	20/44	20/25-20/66
Screen distance acuity	20/19	20/13-20/25	20/30	20/20-20/40
Contrast-sensitivity	1.99	1.95-2.20	1.94	1.85-1.95
Years of education	14.2	12 – 18	14.8	11 – 24
Hours spent reading/week	11.4	6–34	15.8	4-42

Table 2.2. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 1. Appropriate correction was applied to calculate acuity at the distances used.

Apparatus. An SR Research tower mounted EyeLink 1000 eye tracker with a spatial resolution of .01° was used to record gaze location every millisecond using corneal reflection and pupil tracking. This gaze information was delivered to the display computer through a high-speed Ethernet link. The refresh rate of the display screen was 120Hz. The time from when the eye moved into a region until the display change was executed was around 6-12ms. Viewing was binocular, but only the right eye was tracked. A 20-inch ViewSonic CRT monitor with a screen resolution of 1024x768 was used to display the stimuli. Text was presented in monospaced Courier New font as black text on a very light grey background. Sentences always started at the same location half way down the screen, beginning on the far left. At the 80cm viewing distance used in the study, 3.3 characters subtended one degree of visual angle and therefore were of normal size for reading (Rayner & Pollatsek, 1989).

Materials & Design. The experiment was a 2 (age: young, older) x 6 (window condition: normal next, Left 1wd-Right all, Left 0wd-Right all, one-word window, Left all-Right 0wd, Left all-Right 1wd) mixed design. Stimuli consisted of 108 experimental sentences plus 12 practice sentences (from White, Staub, Drieghe, & Liversedge, 2011). Sentences were 10-14 words in length (*M*= 12.0). A gaze-contingent moving-window

(McConkie & Rayner, 1975) was used to manipulate the amount of information available to the reader. Each word formed a separate region, and the region within which the reader's gaze fell was used to determine the location of the moving-window[1].

These sentences were presented in one of six conditions (examples in Figure 2.1). Outside of this window of normal text, the letters of the words contained an orthography replacement (in which the letters within words were replaced with orthographically similar letters). Each letter's most orthographically similar letter was chosen using Bouma's (1971) confusability matrices, these matrices indicate degree of perceptual similarity and consider properties of a letter such as ascending and descending parts and height-to-width quotient. Each participant viewed each sentence, and a Latin square design ensured that within each participant group each sentence was presented equally often in each of the window conditions and each participant saw an equal number of items in each condition. Approximately one-third of the sentences were followed by a comprehension question.

Procedure. At the beginning of the experiment participants read a set of written instructions, completed a consent form and answered a series of questions regarding their reading habits, their education and whether they had any history of dyslexia or eye disease/disorder. Visual acuity was assessed prior to commencing the eye tracking session. Participants were instructed that their task was to read and understand each of the sentences to the best of their ability before moving on. A chin and forehead rest were used to minimise head movements, with the height and position adjusted as appropriate for each participant.

Participants pressed a button on a games pad to indicate when they had finished reading each sentence. For the sentences that were followed by a comprehension question, immediately once the participant pressed the button indicating that they were finished reading, the sentence was replaced with a simple yes/no question, which required a response (button press) before continuing.

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[1]The window in each condition included the word or words for the relevant window plus the spaces following and preceding the word. In order to determine which word was being fixated, the cut-off point was placed half a character before the word (i.e. in the space preceding the word). Incorporating only half of the preceding space reduced the chances of readers' gaze falling on the boundary of two interest areas, as this would have resulted in flicker. When the word was one or two letters in length, it was incorporated with the following word.

```
Normal Text: All text to left and right

She hated the awful music that was coming from the house next door.
                      *
One-Word Window: Replaced text to left, replaced text to right

Ako ksfob fko svtwi music fksf vsa eunlmy tcun fko kuwao mozf buuc.
                      *
Left 1wd-Right all: One word to left, all text to right

Ako ksfob fko awful music that was coming from the house next door.
                      *
Left 0wd-Right all: Replaced text to left, all text to right

Ako ksfob fko svtwi music that was coming from the house next door.
                      *
Left all-Right 0wd: All text to left, Replaced text to right

She hated the awful music fksf vsa eunlmy tcun fko kuwao mozf buuc.
                      *
Left all-Right 1wd: All text to left, one word to right

She hated the awful music that vsa eunlmy tcun fko kuwao mozf buuc.
                      *
```

Figure 2.1. An example sentence in each of the conditions. The asterisk (*) represents the location of the reader's gaze.

Prior to the presentation of each trial, a three-point horizontal calibration and validation procedure extending the area of the longest sentence was conducted to ensure that the degree of error for all points was 0.35° or lower. Further validation checks of the same three points were conducted prior to each trial. Re-calibrations were carried out as necessary. At the start of each trial a fixation point was presented in the centre left of the screen at the position of the start of the line of text. Once participants accurately fixated on the cross, the sentence was automatically presented, with the first letter of the sentence replacing the fixation cross.

Analyses. Following standard procedures, fixations shorter than 80ms or longer than 1,200ms were discarded. This accounted for 2.6% of the data. The remaining data were analysed using Analysis of Variance (ANOVA, see Chapter 1, Section 1.3.4) firstly with factors age (young or older) and window condition (normal next, Left 1wd-Right all, Left 0wd-Right all, one-word window, Left all-Right 0wd, Left all-Right 1wd). The analyses are global analyses conducted incorporating eye-movements across the sentence. Variance was computed across participants (F_1) and items (F_2) and the Greenhouse-Geisser correction was used where appropriate (although uncorrected degrees of freedom are presented for simplicity). For all analyses, the design was mixed for F_1 analyses and within-items for F_2 analyses. Pairwise comparisons were performed using the Bonferroni correction. *t*-tests were carried out to examine the size of the age effect in the normal text condition for all measures (these results are detailed in the text). Independent samples *t*-tests were conducted for the participant analyses (t_1) and paired samples *t*-tests for the item analyses (t_2). Effect sizes were computed using partial eta squared for ANOVA analyses and Cohen's d for t-tests.

The following sentence-level measures were examined: sentence reading time, average fixation duration, number of regressive saccades, progressive saccade length and number of first-pass skips, first-pass reading time and rereading time (all measures were calculated as defined in Chapter 1, Section 1.3.4). All participants achieved high comprehension accuracy in the experiment (at least 85%) and did not differ by age ($p>.05$).

2.2.2 Results

Effects of age in the normal text condition. Table 2.3 presents means for these measures. Age-group effects for the normal text conditions are examined prior to examining the effects of the different moving window conditions. Compared to the young adults, the older adults produced numerically longer sentence reading times ($t_1(34)= 1.31$, $p= .20$, d= .44; $t_2(107)= 5.63$, $p< .001$, d= .64), longer fixations ($t_1(34)= 2.38$, $p< .05$, d= .80; $t_2(107)= 8.16$, $p< .001$, d= .94), more regressive saccades ($t_1(34)= 1.66$, $p= .11$, d= .63; $t_2(107)= 5.15$, $p< .01$, d= .55), longer progressive saccades ($t_1(34)= 4.40$, $p< .01$, d= 1.36; $t_2(107)= 16.59$, $p< .001$, d= 2.53), skipped words more often during first-pass reading ($t_1(34)= 2.09$, $p< .05$, d= .69; $t_2(107)= 8.46$, $p< .01$, d= .88) and spent more time rereading ($t_1(34)= 3.20$, $p< .05$, d= .80; $t_2(107)= 8.20$, $p< .01$, d= .90). However young and older adults produced similar first-pass reading times and made a similar number of progressive saccades (*p*s> .05). This experiment therefore produced evidence of age-related reading difficulty and skipping results in line with the notion of risky reading (described in Chapter 1, Section 1.3.2; e.g. Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan, & Paterson, 2014; McGowan, White, & Paterson, 2015; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006).

2(age) x 6 (window condition) analyses. ANOVA statistics for these analyses are summarised in Table 2.4. Graphs for key measures can be found in Figures 2.2-2.5. There were main effects of window condition for all measures. Limiting the amount of parafoveal orthographic information available to readers resulted in longer reading times (both on first-pass and rereading), longer fixations, more regressive saccades, more progressive saccades which were also shorter in length, and fewer first-pass skips. These results indicate that both groups of readers make use of parafoveal orthographic information throughout the reading process in line with previous findings for young adults (McConkie & Rayner, 1975, 1976; Rayner, & Bertera, 1979; Rayner et al., 1982). Main effects further interacted with age in sentence reading times, fixation durations, number of regressive saccades, and rereading times (and in items analyses only for first-pass reading time, progressive saccade length and number of progressive saccades). To investigate these interactions and to explore the size of the perceptual span for both age-groups, pairwise-comparisons were undertaken comparing each condition to the normal text condition for each age-group. These comparisons revealed that compared to normal, removing all information to the right of fixation (Left all-Right 0wd) produced longer sentence reading times, longer fixation durations, more progressive and regressive saccades, shorter progressive saccades, fewer first-pass skips, longer first-pass reading times and rereading times (all *p*s< .05). Removing orthographic information beyond word n+1 (Left all-Right 1wd) showed less disruption than removing all information to the right of the fixated word (Left all-Right 0wd), but still produced longer sentence reading times, more progressive saccades, longer first pass reading times and fewer first-pass skips than normal for both groups (all *p*s< .05).

	Normal	Left 1wd-Right all	Left 0wd-Right all	One-word	Left all-Right 0wd	Left all -Right 1wd
Sentence reading time (ms)						
Young	2416 (100)	2534 (133)	3218 (172)	4422 (188)	3694 (203)	2595 (106)
Older	2751 (236)	2836 (230)	3699 (258)	5615 (337)	4065 (291)	2940 (261)
Fixation duration (ms)						
Young	222 (4)	224 (4)	237 (4)	263 (6)	250 (5)	226 (4)
Older	239 (6)	239 (6)	245 (6)	267 (7)	256 (7)	244 (6)
Progressive saccade length (characters)						
Young	7.3 (0.2)	7.5 (0.2)	7.2 (0.2)	6.1 (0.2)	6.1 (0.2)	7.0 (0.2)
Older	9.5 (0.5)	9.2 (0.5)	9.3 (0.5)	7.5 (0.3)	7.6 (0.4)	8.7 (0.5)
Number of progressive saccades						
Young	8.2 (0.3)	8.4 (0.3)	9.4 (0.4)	11.7 (0.4)	10.9 (0.4)	8.7 (0.3)
Older	7.7 (0.5)	7.9 (0.4)	9.2 (0.6)	12.6 (0.6)	10.3 (0.5)	8.2 (0.5)
Number of regressive saccades						
Young	1.7 (0.2)	2.0 (0.3)	2.8 (0.3)	3.1 (0.3)	2.3 (0.3)	1.8 (0.2)
Older	2.4 (0.3)	2.4 (0.3)	4.0 (0.4)	5.5 (0.5)	3.3 (0.4)	2.3 (0.3)
First-pass reading time						
Young	1842 (60)	1895 (61)	2057 (69)	2864 (126)	2751 (115)	2027 (67)
Older	1828 (125)	1890 (150)	1964 (115)	2682 (143)	2556 (155)	1983 (137)
Number of first-pass skips						
Young	4.0 (0.2)	4.0 (0.2)	3.8 (0.1)	2.4 (0.2)	2.4 (0.2)	3.6 (0.2)
Older	4.7 (0.3)	4.6 (0.3)	4.4 (0.3)	2.9 (0.2)	3.0 (0.2)	4.2 (0.3)
Rereading time						
Young	396 (61)	462 (76)	877 (99)	1134 (111)	670 (103)	399 (46)
Older	643 (114)	631 (103)	1263 (141)	2088 (229)	987 (144)	660 (126)

Table 2.3. Means for each age group in each condition. Standard errors are shown in parentheses.

Thus, readers required up two words to the right of fixation to read normally (McConkie & Rayner, 1975; Rayner & Bertera, 1979; Rayner et al., 1982). Removing orthographic information to the left of the fixated word (Left 0wd-Right all) produced longer sentence reading times, longer fixation durations, more progressive and regressive saccades, fewer first pass skips, and longer first-pass reading times and rereading times than normal for both groups. These findings demonstrate the importance of text to the left of the fixated word (Apel et al., 2012; Binder et al., 1999; Veldre & Andrews, 2014). However, there were no differences between normal text and text for which information beyond the word to the left of the fixated word was removed (Left 1wd-Right all), indicating that readers processed text no further to the left than word n-1. Crucially, this pattern of effects was the same for both young and older adults. These comparisons therefore suggest a perceptual span which is of similar size for both age groups.

As the pairwise comparisons did not reveal any age differences in the effects of the window condition, in order to verify how effects of age modulate reading behaviour in each condition, the size of the age effect (i.e. the mean of the older adults minus the mean of the young adults) was entered as the within-subjects dependent variable in additional analyses. This was restricted to F_2 analyses, as in the F_1 analyses age was a between-subjects variable. Any differences in the size of the age effect between the different conditions would indicate that young and older adults were affected differently by the moving window manipulation (these analyses are reported in the text).

These analyses revealed that the size of the age effect differed across conditions in sentence reading time: F_2 (5, 535)= 13.54, η_p^2= .112, p< .001, number of regressive saccades: F_2 (5, 535)= 21.41, η_p^2 = .167, p< .001, rereading time: F_2 (5, 535)= 20.38, η_p^2= .278, p< .001, and average fixation duration F_2 (5, 535)= 5.84, η_p^2= .052, p< .001. Follow-up pairwise comparisons revealed that the size of the age effect in the one-word condition increased significantly in sentence reading times, number of regressive saccades and rereading times compared to the normal text condition (*ps*<.001). This can be seen in Figure 2.2, 2.4 and 2.5. Older adults therefore experienced greater reading difficulty than young adults when correct orthographic information to the right and left of a fixated word was unavailable. As first-pass reading times were similar for young and older adults, the increased sentence reading times likely reflects this greater number of regressive saccades and longer rereading times in the one-word condition.

Further, for average fixation durations the size of the age effect differed significantly from the normal condition when only the fixated word was presented normally (one-word condition) and when only the fixated word and words to the left of the fixated word were presented normally (Left all-Right 0wd condition) (ps< .01). In these conditions the size of the age effect decreased such that fixation durations increased more for young adults than for older adults. This can be seen in Figure 2.3. Crucially, no other moving-window conditions produced age effects that differed from normal. It therefore appears that young and older adults gained similar benefits when orthographic information was shown normally to the right or left of fixation and these analyses do not provide any evidence that the perceptual span is smaller for older adults. Overall, these results suggest young and older adults have a perceptual span which is similar in size and symmetry, but that there may be subtle differences in the way that young and older adults respond to the removal of parafoveal orthographic information[2].

[2] Given the particularly complex design of the current experiment and the inconsistent results of previous experiments, to verify this lack of an age-related difference in span size, additional 2 (age) x 2 (direction) x 2 (size) analyses were undertaken for the asymmetric window conditions: Left 1wd-Right all, Left 0wd-Right all, Left all-Right 0wd and Left all-Right 1wd. These results revealed similar effects of direction for both age-groups. Further, older adults gained greater benefit from a larger window size (Left 1wd-Right all and Left all-Right 1wd) in rereading times, while young adults gained greater benefit from a larger window size (Left 1wd-Right all and Left all-Right 1wd) in fixation durations and first-pass reading times. In line with 2x6 analyses these results suggest that the perceptual span is similar in size for both age groups, but that the behavioural response to the removal of this information differs (see Appendix B).

		Sentence Reading Time		Fixation Duration		Progressive Saccade Length		Number of Progressive Saccades		Number of Regressive saccades	
		F1	*F2*	*F1*	*F2*	*F1*	*F2*	*F1*	*F2*	*F1*	*F2*
Age	*F*	4.02*	128.79*	2.45	158.71*	16.01*	1695.95*	.033	1.68	6.86*	242.47*
	η_p^2	.106	.546	N/A	.597	.320	.941	N/A	N/A	.168	.694
Window Condition	*F*	112.19*	204.29*	83.49*	82.97*	79.09*	203.59*	125.23*	226.31*	50.77*	94.57*
	η_p^2	.767	.656	.711	.437	.699	.655	.786	.679	.599	.469
Age x Window Condition	*F*	6.21*	13.54*	3.636*	5.84*	2.91	5.90*	6.29	11.55*	10.24*	21.41*
	η_p^2	.154	.112	.097	.052	N/A	.052	N/A	.097	.231	.167

Table 2.4. ANOVA statistics for global measures. * indicates significance at the $p < .05$ level. Degrees of freedom F1= 1,34, F2= 5, 535. Table continues on next page.

		First-pass Reading Time		Number of First-pass Skips		Rereading Time	
		F1	***F2***	***F1***	***F2***	***F1***	***F2***
Age	*F*	0.34	28.66*	4.11*	288.08*	6.22*	124.18*
	η_p^2	N/A	.351	.108	.845	.155	.701
Window Condition	*F*	173.31*	222.91*	133.16*	271.80*	54.09*	103.02*
	η_p^2	.836	.808	.797	.837	.614	.660
Age x Window Condition	*F*	0.31	4.97*	0.29	.656	8.08*	20.38*
	η_p^2	N/A	.086	N/A	N/A	.192	.278

Table 2.4. continued.

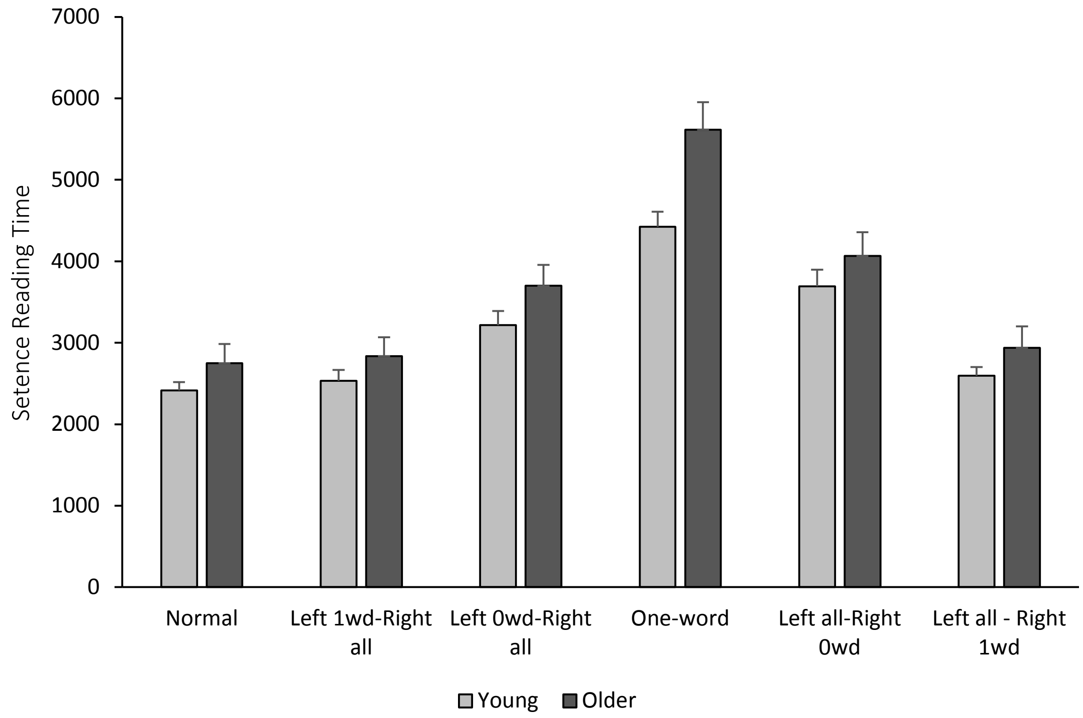

Figure 2.2. Mean sentence reading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

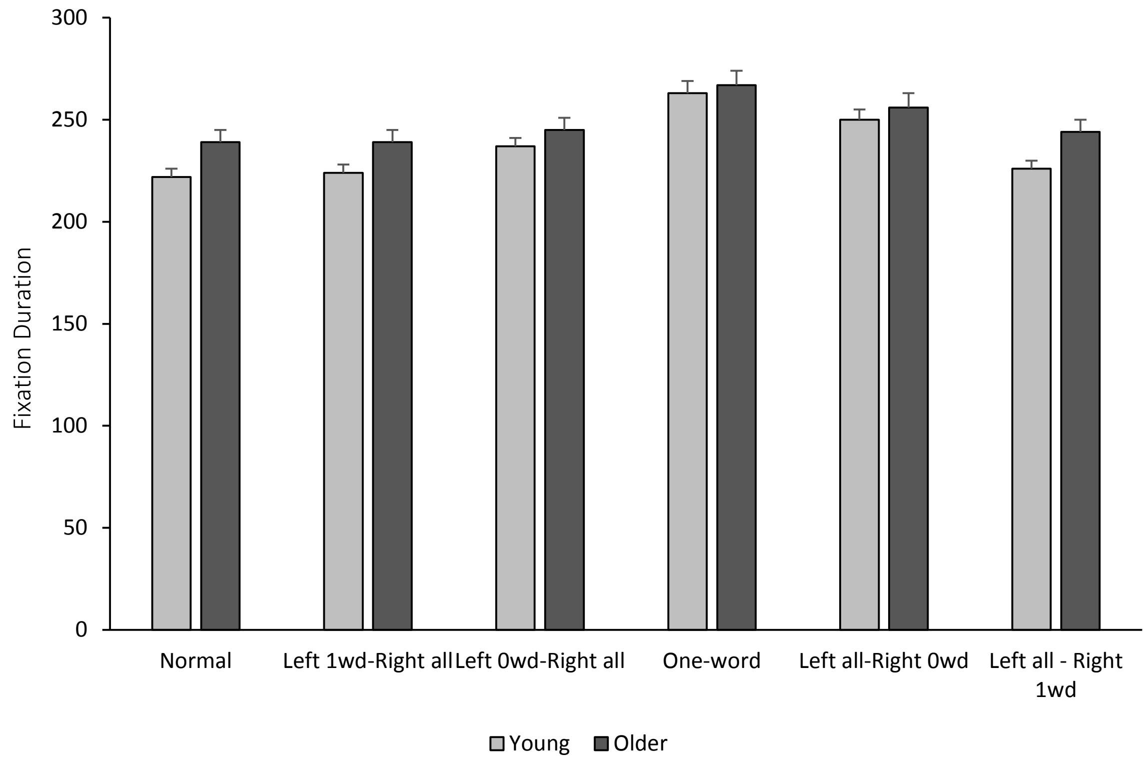

Figure 2.3. Mean fixation durations (ms) for each age-group in each condition. Error bars correspond to one standard error.

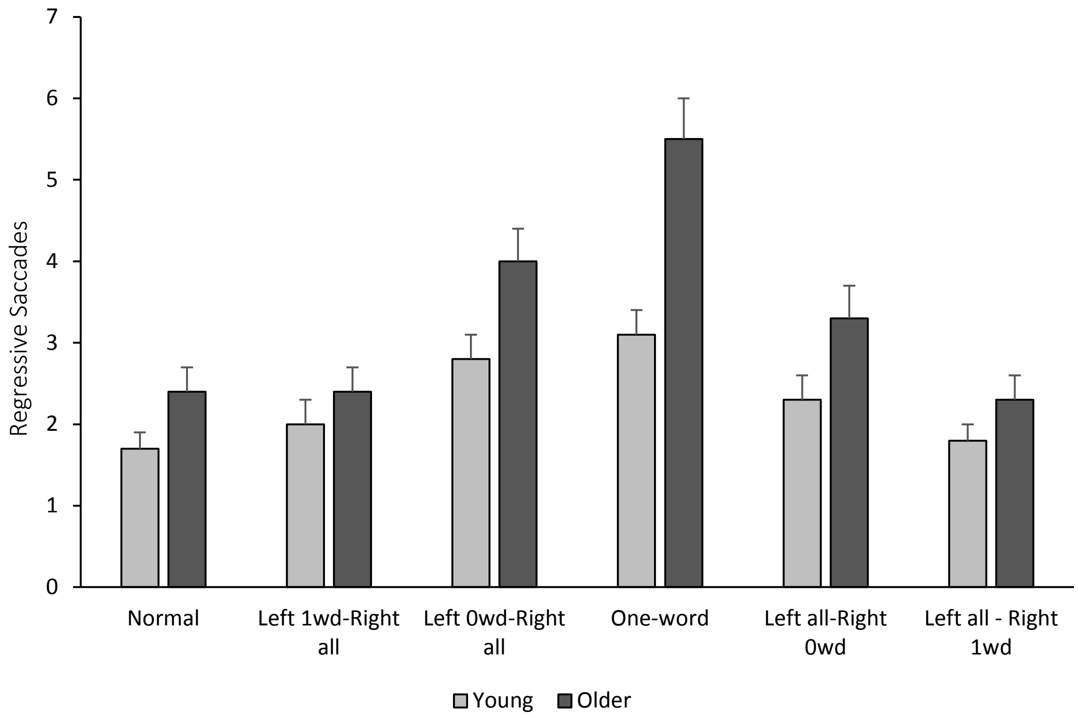

Figure 2.4. Mean number of regressive saccades for each age-group in each condition. Error bars correspond to one standard error.

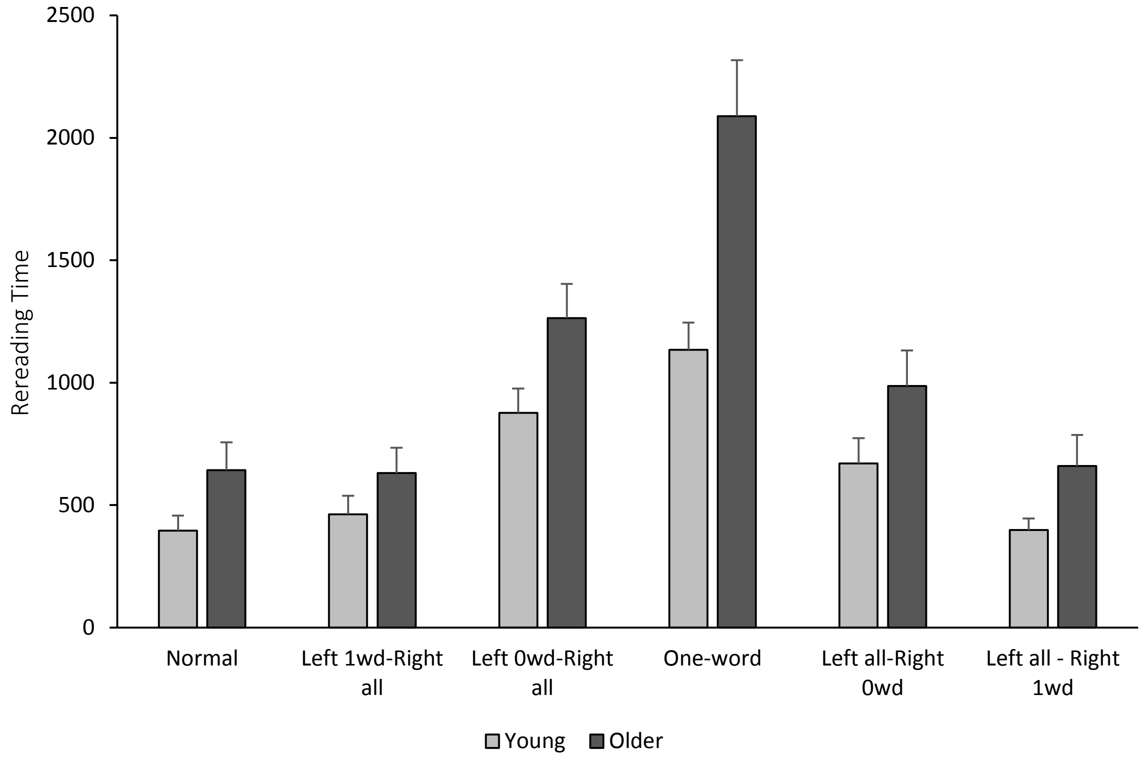

Figure 2.5. Mean rereading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

2.3 Discussion

In the present experiment a gaze-contingent moving-window was employed to explore parafoveal processing in young and older adults. This study yielded 4 key findings: (1) Adult age differences in reading: Older adults found reading more difficult and displayed a typical "risky" pattern of eye movement behaviour. (2) Orthographic parafoveal processing: Both age groups read more slowly when parafoveal orthographic information was not available. These findings provide further insight into the role of parafoveal orthographic processing in normal reading. (3) Age differences in the size of the perceptual span: Older adults were able to make use of parafoveal information across a similar region to young adults and so parafoveal processing does not appear to be impaired in older age. (4) Differences in response to the removal of parafoveal information: There appear to be some subtle differences in the way that young and older adults respond to the removal of parafoveal orthographic information. Each of these key findings will be discussed in turn.

Adult age differences in reading

Effects of adult age were largely consistent with those of previous literature (e.g. Rayner et al. 2006) in that older adults produced numerically longer sentence reading times, longer fixations, more regressive saccades, more skips during first-pass reading, and longer progressive saccades than young adults in the normal text condition. Although age effects for some measures were not reliable, the overall pattern of eye movement behaviour largely supports the notion that older adults experience greater reading difficulty. These results also support the notion that older adults may engage in "risky" reading to compensate for this greater difficulty.

Orthographic parafoveal processing

The present experiment revealed that the reading of both young and older adults is severely compromised when orthographic information cannot be obtained in the parafovea. There were significant main effects of window condition for all measures examined. Removing orthographic parafoveal information resulted in longer reading times (both during first-pass and rereading), longer fixations, a greater number of progressive and regressive saccades and shorter progressive saccades. These effects were largest in the one-word condition, indicating that the effect on reading behaviour is greater when more information is removed.

For young adults, these findings are consistent with previous demonstrations of the important role of parafoveal orthographic information during reading (Schotter, Angele, & Rayner, 2012). Importantly, the present study demonstrates that parafoveal processing continues to play a crucial role in normal reading for older adults. Thus, despite the visual declines outside of central vision during older age which may reduce the quality of visual information that can be obtained in the parafovea (Crassini et al., 1988; Scialfa et al., 2013), as well as the cognitive changes which may further reduce the efficiency with which non-foveal information can be processed (Ball et al., 1988; Sekuler, & Ball, 1986; Sekuler et al., 2000), readers continue to process text in the parafovea during older age.

Age differences in the perceptual span

A key concern of the current experiment was to examine whether the perceptual span differs in size and symmetry between young and older adults. The current experiment found, in contrast to some previous studies (Rayner et al., 2009; 2010; 2014- foveal mask condition), no evidence of impaired parafoveal processing. These results are indicative of an overall asymmetry in processing in line with previous research (McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979; Underwood & McConkie, 1985). However, these results are at odds with the notion of a more symmetric perceptual span in older adults (Rayner et al., 2009; 2010).

For both young and older adults, reading speeds returned to normal when one word to the left of fixation and all words to the right of fixation were available, however, reading speeds remained above normal when one word to the right of fixation and all words to the left of fixation were available. This indicates that both the young and older adults benefitted from having orthographic information for at least two words to the right of the fixated word but only required one word to the left of fixation in order to read normally. Crucially, these results indicate that in spite of age related visual difficulties, such as decreased sensitivity to fine visual detail and increased sensitivity to the effects of visual crowding (Scialfa et al., 2013), the size of the perceptual span is maintained in older age.

Differences in response to the removal of parafoveal information

Although the results indicate an equally asymmetric span for the two age groups, removing parafoveal orthographic information produced a differential pattern of effects for young compared to older adults. Indeed, removing this information for all text other than the fixated word produced a larger increase in fixation durations for the young than the older adults and a larger increase in the number of regressive saccades and time spent rereading for the older than the young adults. The findings for the young and older adults taken together may suggest that while both older and younger adults benefit from the availability of parafoveal orthographic information, their behavioural responses to the removal of this information differ. These results indicate that young and older adults have a very similar sized span, but that there may be subtle differences in the way that information is used within this span. These differences may in part stem from young and older adults adopting different reading strategies (discussed further in Chapter 6, Section 6.2.4).

Further work is needed to understand why findings differ across studies. It seems likely that both methodological differences (e.g. stimuli used, type of mask employed) and participant characteristics (vision, cognitive skills) may play a role. In particular, the use of the letter “x” as a letter replacement (as in Rayner 2009; 2014) may prove distracting and could interfere with normal reading, particularly for older readers who typically have difficulty ignoring distracting text (Kemper & McDowd, 2006). Further, a careful examination of the stimuli used in each experiment may be fruitful (unfortunately, in many cases, stimuli is not readily available) as the characteristics of these stimuli may affect the results. For example, the use of stimuli that generates more skips may result in greater adult age differences appearing in moving-window experiments, due to greater shifts of attention to the left (Apel et al., 2012). However, in boundary experiments a short word n or n+1 may increase the likelihood of n + 1 and n+2 processing for both young and older adult readers (Risse & Kliegl, 2011). Previous research (Payne & Stine-Morrow, 2012) has also demonstrated that certain types of stimuli may inhibit older adults’ parafoveal processing (in this case, when sentence wrap-up increases cognitive workload). Risse and Kliegl (2011, see also Grabbe & Allen, 2013) suggest that distribution of attention in older and younger adults can offset any age-related limitations in the ability to extract parafoveal information to the right of fixation and older adults may prioritise parafoveal processing (while making longer individual fixations) as a compensatory strategy to maintain reading speeds (discussed further in Chapter 6).

In addition, in most of these experiments, participants are reported as having normal visual acuity (note, this was not tested in Whitford & Titone, 2016 and in other experiments acuity is tested only foveally), however, in Rayner et al.'s 2009 and 2010 studies, performance on a test of language and cognitive skills varied significantly across participants. The role of individual cognitive skill may be an important consideration for future research as research with young adults (Choi, Lowder, Ferreira, & Henderson, 2015) has previously demonstrated that individual differences in language skill modulate the size of the perceptual span. Further, in Rayner et al. (2009) although the authors conclude that older adults have a more symmetric perceptual span than young adults, older adults produced reading times that were considerably higher than reading times in the normal text condition when only one word to the right of fixation or two words to the right of fixation were available (around 500ms longer in both cases) and Rayner et al. (2010) found that older adults' processing of n+1 is only attenuated on a subset of fixations. This further suggests that these results may not provide the full story.

Importantly, by conducting a careful examination of both the size and symmetry of the perceptual span, in which the parafoveal processing orthographic information was assessed, and in which a more natural looking orthographic replacement condition was chosen, the present study was able to produce a more detailed investigation of how parafoveal processing changes during older age

2.4 Conclusion

In conclusion, while previous studies have produced inconsistent results regarding the size of the perceptual span in older age, the findings of the current experiment indicate that parafoveal processing in older age is not impaired. Overall, the findings suggest that young and older readers have a perceptual span of similar size and symmetry. However, while both older and young adults both benefit from the availability of parafoveal orthographic information, their behavioural responses to the removal of this information differ, suggesting that there may be subtle differences in the way that information is used within this span. Overall, these results indicate that reduced parafoveal processing may not be a key factor in the reading difficulty that older adults experience. Experiment 1 has examined the very early processing that occurs before a word is fixated. Moving on from this, Experiment 2 and Experiment 3 address an important issue relating to the visual processing of text and will focus on a manipulation of stimulus quality both foveally and parafoveally.

Chapter 3:

Effects of ageing and stimulus quality on reading

Due to the sensory declines that occur with advancing age, middle-aged and older readers may be especially vulnerable to reductions in the stimulus quality of text. However, this has not been tested directly. Accordingly, Chapter 3 reports two experiments that examine the effects of reduced stimulus quality on the eye movements of young (18-24 years), middle-aged (41-51 years) and older (65+ years) adult readers. In Experiment 2, participants read sentences that contained a high- or low-frequency critical word. Sentences were presented normally or with contrast reduced such that words appeared faint. Experiment 3 further investigated the effects of reduced stimulus quality using a gaze-contingent technique to present upcoming text normally or with contrast reduced. In both experiments, typical patterns of age-related reading difficulty were observed. In addition, eye movement behaviour was disrupted more for older than younger adults when all text (Experiment 2) or just upcoming text (Experiment 3) appeared faint. Furthermore, in Experiment 2 there was an interaction between stimulus quality and word frequency, such that readers fixated faint lower frequency words for disproportionately longer. Crucially, this effect was similar for readers of all age groups. Thus, although older readers suffer more from reduced stimulus quality, this additional difficulty appears to primarily affect their visual processing of text. This novel study is the first to examine these issues in natural reading with using eye movement measures for middle-aged and older readers. The findings of these two experiments have important implications for understanding the role of stimulus quality on reading behaviour across the lifespan.

3.1 Introduction

Experiments 2 and 3 examine the impact of reducing text contrast on the reading of young, middle-aged and older adults. Numerous studies with young adult participants show that words are more difficult to recognise when stimulus quality is reduced by presenting text in lower contrast so that words appear faint (e.g. Becker & Killion, 1977). Some studies have also investigated the effects of reduced visual contrast on the reading performance of individuals with visual impairments (e.g. Legge, Rubin, Pelli & Schleske, 1985). However, few studies have investigated effects for typical older adult readers (e.g. Mitzner & Rogers, 2006), although it is well-established that sensory declines that begin early in middle-age and manifest more severely in older age might cause readers to also experience greater difficulty. Indeed, older adults commonly self-report difficulties associated with contrast in visual quality of life assessments, such as problems seeing in dim light and distinguishing between dark colours (Kosnik, Winslow, Kline, Rasinsk, & Sekuler, 1988). Consequently, as text encountered in everyday reading can vary substantially in contrast (e.g., due to print or display quality) and reading often occurs in sub-optimal luminance (Charness & Dijkstra, 1999), changes in visual contrast may have important consequences for older adults' reading performance. Accordingly, the present study provides the first examination of adult age differences in the effects of reduced visual contrast on eye movement behaviour, and effects of stimulus quality on lexical processing.

Text stimulus quality

Several studies have investigated the effect of stimulus quality on eye movement behaviour in young adult readers by manipulating the contrast of a single critical word within a sentence (Drieghe, 2008; Glaholt, Rayner, & Reingold, 2014; Reingold & Rayner, 2006; Sheridan & Reingold, 2013; Wang & Inhoff, 2010; White & Staub, 2012) or manipulating the contrast of the whole sentence (Hohenstein & Kliegl, 2014; Liu, Li & Han, 2015; Jainta, Nikolova, & Liversedge, 2017; White & Staub, 2012). These studies demonstrated that reading times are increased when text contrast is reduced. However very few studies have examined effects of text stimulus quality on reading behaviour for older adults (Mitzner & Rogers, 2006, see also Madden, 1988; Speranza, Daneman, & Schneider, 2000), and no studies have carried out a detailed assessment of effects of stimulus quality on eye movement behaviour during reading for older adults.

Given the visual declines that occur in older age, such as decreased contrast sensitivity (Crassini, Brown, & Bowman, 1988) and a loss of sensitivity to fine visual detail (such as letter features or individual letters) (Crassini et al. 1988; Elliott, Whitaker, & MacVeigh, 1990; Owsley, Sekuler & Siemsen, 1983, for a discussion of age related changes in visual function, see Chapter 1, Section 1.2.1) it is reasonable to speculate that high stimulus quality may be especially important for older adults. Indeed, a study by Mitzner and Rogers (2006) in which young and older adults read high, medium and low-contrast sentences presented word-by-word, showed larger effects of text contrast on reading times for older adults compared to younger adults. Additionally, studies employing methods other than contrast reduction to reduce stimulus quality have also shown greater effects of text quality for older than young adults. Madden (1988) found that response times in a lexical decision task (LDT) increased more for older than for young adults when asterisks were placed between adjacent letters, while Paterson, McGowan and Jordan (2013a,b) found that filtering the spatial frequency content of text affected young and older adults differently, with older adults experiencing greater reading difficulty than young adult readers when text lacked its normal full complement of spatial frequencies.

Many of the changes in visual abilities shown for older adults begin in middle-age. In particular, a loss in contrast sensitivity has been shown to begin around 40-50 years of age and become more pronounced with advancing age (Schefrin, Tregaer, Harvey & Werner, 1999; Owsley et al., 1983; Owsley, 2011). Further, some studies have hinted at a slowdown in reading under normal reading conditions for those in middle-age (e.g. 35-59 years) (Soederberg Miller, 2009; Calabrèse et al., 2016; see also, Teramoto, Tao, Sekiyama, & Mori, 2012), although none have employed eye-tracking methods to examine these differences in detail. Therefore, it could be that poor stimulus quality is also more detrimental for middle-aged readers compared to younger adults. An important consideration in the current study was to establish at what point during the adult lifespan low-contrast text becomes problematic for reading. The present study expands on previous research by exploring a variety of eye movement measures to examine the impact of reduced stimulus quality on the reading of middle-aged and older adults as well as young adults. Further, as is discussed in the next section, this is the first study to examine the joint influence of stimulus quality and lexical processing for older adults.

Stimulus quality and lexical processing

There has been longstanding interest in how manipulations of the visual quality of text affects word recognition. A particular concern is to establish if reductions in stimulus quality affect only the early encoding of visual and orthographic features, or also the lexical processing of words (e.g. Becker & Killion, 1977). Effects of word frequency (Chapter 1, Section 1.4.2) on eye movement behaviour during reading can provide an index of lexical processing difficulty (Inhoff & Rayner, 1986; Rayner, Sereno, & Raney, 1996). Additive effects of contrast and word frequency might indicate these variables influence separate processing stages, while interactive effects might suggest they influence a common stage (Sternberg, 1969; but see McClelland, 1979). As noted in Chapter 1, Section 1.4.5 older adults have sometimes been shown to produce larger word frequency effects than young adults, by producing disproportionately longer reading times on words that have a lower frequency of written usage (Kliegl, Grabner, Rolfs & Engbert, 2004; McGowan, White & Paterson, 2015; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Whitford & Titone, 2017) in line with the possibility that older adults find lexical processing more difficult. Crucially, the present study will further examine how stimulus quality affects word recognition processes for middle-aged and older readers.

Isolated word recognition studies have produced varying results depending on the methodology employed, with strongly additive effects found in LDT (Balota & Abrams, 1995; Becker & Killion, 1977; Plourde & Besner, 1997; Stanners, Jastrzembski, & Westbrook, 1975; Yap & Balota, 2007, but see Balota, Aschenbrenner, & Yap, 2013) while others have shown interactive effects for naming and semantic categorisation tasks (O'Malley, Reynolds, & Besner, 2007; Yap & Balota, 2007). These differing results suggest the influence of stimulus quality depends on specific task requirements (Yap & Balota, 2007; Yap, Balota, Tse & Besner, 2008).

Studies of eye movement behaviour during sentence reading have also shown interactive patterns of results when the stimulus quality and word frequency of a single critical word within a sentence is manipulated. Sheridan and Reingold (2013) showed interactive effects in early measures such as the duration of initial fixations, with larger word frequency effects for faint words compared to normally presented words. This suggests that stimulus quality has an early influence on lexical processing. However, additive effects have been shown for studies for which the stimulus quality of the entire sentence was manipulated (Liu et al., 2015; Jainta et al., 2017).

Liu et al. (2015) investigated interactions between contrast and word frequency during the reading of Chinese in two experiments, one using faint critical words, and a second using entirely faint sentences. They reported weak interactive effects in single-fixations and gaze-durations when critical words were faint, but only additive effects when entire sentences were faint. They concluded that stimulus quality and word frequency influence separate stages of processing for readers of Chinese and argued that the weak interactive effects seen when the critical word was faint were artefactual. However, this study also employed a very low level of contrast, and so either language factors or visual display factors may underlie these results. Further, in Jainta et al., (2017), all nouns were capitalised (as is the norm for German nouns), and so again, language differences may play a role in these results. This is discussed further in the General Discussion (Section 3.4).

To summarise, studies of effects of stimulus quality on lexical processing during sentence reading for middle-aged and older adult readers are lacking, and the results of previous work for younger adults is mixed. One possibility is that the manipulation of the stimulus quality for a single word in the text may serve to “highlight” this word, and may trigger processes that are not typical of normal reading (White & Staub, 2012). Therefore, in the present study the stimulus quality of entire sentences was manipulated.

3.2 Experiment 2

Whether middle-aged and older readers experience particular difficulties compared to young adults when reading low-contrast text has not been examined in detail. Previous research examining the role of stimulus quality on lexical processing for young adults is mixed and no studies have examined these issues for middle-aged readers. Further, previous studies examining the effects of reduced contrast on older adults reading have not employed eye-tracking methods and have not explored interactions with lexical processing. Accordingly, the present study aimed to: 1) Examine measures of eye movement behaviour to provide more detailed insights into the time course of effects of text stimulus quality for older adults. 2) Examine effects of stimulus quality for middle-aged readers. 3) Examine the effect of stimulus quality on lexical processing by including a manipulation of word frequency.

Two experiments are presented in which participants read sentences presented normally or with contrast reduced so that words appeared faint. In line with previous work it was predicted that reading times would be longer for sentences presented in low- compared to high-contrast. If older readers are especially vulnerable to reductions in stimulus quality, reading faint text will disrupt eye movement behaviour to a greater extent than for young adults. Middle-aged readers may also show greater vulnerability to reduced stimulus quality, but to a lesser extent than older adults. A manipulation of word frequency for a critical word is also included. If reduced text contrast increases the difficulty of lexical processing then there should be interactions between word frequency and stimulus quality, with larger effects of word frequency for faint text (in line with Sheridan & Reingold, 2013). It could be that these effects may be exacerbated for middle-aged and older readers due to visual declines. Alternatively, it could be that the manipulation of stimulus quality for the entire sentence, rather than just a critical word, may result in a different pattern of effects, as shown by Lui et al. (2015) and Jainta et al. (2017).

3.2.1 Method

Participants. Sixteen young adults (*M*= 19.2, range= 18-22 years, 10 female), sixteen middle-aged adults (*M*= 46.4, range= 41-51 years, 9 female) and sixteen older adults (*M*= 69, range= 65-79 years, 9 female) were recruited from the University of Leicester and the local community. Participation criteria were the same as in Experiment 1. Participant characteristics are summarised in Table 3.1. Both the young adults and the middle-aged adults had higher acuity than the older adults ($ps<.05$). Young adults (but not middle-aged adults) also had better contrast sensitivity than the older adults ($p<.05$). Participants were closely matched on years of education and all groups engage in a similar amount of reading activity ($ps>.05$). In addition to the sixteen older participants included in the analyses, six older adults were excluded due to an inability to read the low-contrast text.

	Young		Middle-Aged		Older	
	Mean	Range	Mean	Range	Mean	Range
High contrast near acuity	20/17	20/14-20/20	20/19	20/14-20/25	20/26	20/14-20/35
Low contrast near acuity	20/25	20/20-20/32	20/28	20/22-20/40	20/38	20/25-20/50
High contrast distance acuity	20/19	20/17-20/25	20/20	20/17-20/30	20/23	20/17-20/32
Low contrast distance acuity	20/26	20/22-20/33	20/26	20/23-20/35	20/36	20/22-20/53
Screen distance acuity	20/17	20/14-20/25	20/20	20/14-20/26	20/25	20/16-20/32
Contrast-sensitivity	1.97	1.90-2.10	1.95	1.90-2.05	1.94	1.90-1.95
Years of education	15	13-18	14.2	11-18	15.7	12-22
Hours spent reading/week	11.5	2-25	13	2-30	12.4	4-28

Table 3.1. Visual abilities, years of education, and hours spent reading for young, middle-aged and older adults in Experiment 2. Appropriate correction was applied to calculate acuity at the distances used.

Materials and Design. The experiment was a 3 (age: young, middle, older) x 2 (stimulus quality: normal text, faint text) mixed design with an additional x 2 factor of word frequency (high, low) for the critical word analyses. Stimuli consisted of 120 sentences (from White et al., 2018) including a high- or low-frequency four to six letter long critical word (examples in Figure 3.1). This word was placed approximately in the centre of the sentence, and sentences varied in length from 7-15 words. A Latin square design ensured that each participant saw each critical word only once with an equal number of sentences in each condition. 25% of sentences were followed by a comprehension question. The luminance of the white background remained the same across all of the conditions (RGB 255 255 255; 54.25 cd/m^2). The critical words were presented either in high-contrast as black text (RGB 0 0 0; 0.53 cd/m^2) or in low-contrast as light grey text (RGB 217 217 217; 37.66 cd/m^2) [3].

High Contrast-High Frequency:

`He knew that the small room would be really useful for storage.`

High Contrast-Low Frequency:

`He knew that the small crib would be ideal for his baby nephew.`

Low Contrast-High Frequency:

`He knew that the small room would be really useful for storage.`

Low contrast-Low Frequency:

`He knew that the small crib would be ideal for his baby nephew.`

Figure 3.1. Experiment 1. An example sentence in each condition. A box highlights the high/low frequency critical word. This box was not present during the experiment.

Apparatus. Apparatus was the same as in Experiment 1.

Procedure. Before commencing the experiment, the participant's ability to read the low-contrast text was confirmed. The rest of the procedure was the same as in Experiment 1.

Analyses. Following standard procedures, fixations shorter than 80ms or longer than 1,200ms were discarded. This accounted for 1.8% of fixations. The data were analysed using linear mixed effects models (described in Chapter 1, Section 1.3.4). LMEM; Baayen, Davidson, & Bates, 2008). LMEMs were conducted using R (R Core

[3] Using the weber contrast calculation gives a value of 30% of normal contrast for the faint condition in the current study, the same calculation produces a value of 40% for the faint condition in the Sheridan and Reingold (2013) study. Using this calculation to compare across studies reveals that contrast levels between 30-40% of full contrast have been employed by five other studies to date (Glaholt, Rayner & Reingold, 2014; Hohenstein & Kliegl, 2014; Jainta et al., 2016; Sheridan & Reingold, 2013; Wang & Inhoff, 2010). Several other studies e.g. Liu, Li & Han (2015) have used contrast levels much lower than this (in this case 15% of full contrast), however, this level of contrast was deemed too low for use with older adults.

Team, 2015, version 3.2.3) and the lme4 package (Bates, Maechler & Bolker, 2011, package version 1.1-12. Following current practice, a maximal random effects structure was used for continuous measures (following Barr, Levy, Scheepers & Tily, 2013). Participants and stimuli were always specified as crossed-random effects. Generalized linear mixed models were conducted for dichotomous variables [4]. In all of the following experiments, untransformed statistical values are reported. For this experiment and all subsequent experiments, log-transformed values can be found in Appendix C. In all cases the pattern of results is similar for both transformed and untransformed.

For sentence-level measures effects of age are first examined for only the normal (high-contrast) condition (the results for these models are detailed in the text). First, Type II model comparisons were used to determine main effects of age using the ANOVA function of the car package (Fox, Friendly, & Weisberg, 2013). Then individual contrasts were examined using sliding contrasts as defined below. For all of the conditions in the sentence level analyses, age-group, text contrast and their interaction were entered as fixed effects, with frequency additionally included as a fixed effect in the critical word analyses. Results from these LMEM models are reported in tables. Interaction effects were explored further with contrasts between pairs of variables. Contrasts were specified to compare the high and low contrast conditions for each age group, and where appropriate, to compare the high and low word frequency conditions for each level of text contrast and age group. Contrasts to examine effects of age-group (young vs. middle-aged; middle-aged vs. older), text contrast (normal text vs. faint text) and word frequency (high vs. low) were defined using sliding contrasts in the MASS package (Venables & Ripley, 2002) (sliding contrasts were employed both for main effects and to examine interactions). Effects of age were also examined using a young vs. older contrast, however the pattern of results was the same as for the middle-aged vs. older contrast and so, for brevity, these are not reported. For all analyses, t/z values >1.96 were considered significant.

[4] If a model failed to converge, the structure was pruned until convergence was achieved. Sentence-level measures for number of regressive saccades, rereading time, and number of first-pass skips can include zero values, so a small amount (less than one) was added to each zero to allow log-transformation of these data.

Several standard sentence-level measures are presented: sentence reading time, average fixation duration, progressive saccade length, number of first-pass skips and number of regressive saccades. First-pass reading times and rereading times are also reported. Critical word measures are also presented: first-fixation duration, gaze duration, total reading time and skipping probability. Definitions for all reported measures can be found in Chapter 1, Section 1.3.4. All participants achieved a high level of comprehension accuracy in all conditions (Min= 85%).

3.2.2 Results

Sentence-level analyses. Means and standard errors for sentence level eye movement measures are shown in Table 3.2. Effects of age are first examined only for the normal high-contrast text condition. There were main effects of age in sentence reading times (F=2.89, p<.05), number of regressive saccades (F=4.10, p<.05) and rereading time (F=5.05, p<.01). Differences in average fixation duration, progressive saccade length, first-pass reading time and number of first-pass skips did not reach significance (*ps* >.05). Contrasts revealed that compared to middle-aged adults, older adults produced longer sentence reading times (β= 475.58, *SE*= 240.46, t= 1.98), made more regressive saccades (β= 0.65, *SE*= 0.10, t= 2.45), and produced longer rereading times (β= 509.20, *SE*= 167.64, t= 3.04) while the performance of middle-aged adults and young adults did not differ significantly (in all cases t <1.20). These results reflect adult-related reading difficulty for those aged 65+ compared to younger readers, in line with previous research. In contrast previous studies have reported higher skipping rates for older compared to younger adults (e.g. Rayner et al., 2006, Experiment 1, See Appendix A for a comparison). The intermingling of normal and faint sentences may have led older readers to adopt a more cautious reading strategy, reducing skipping rates for both normal and faint text conditions (see General Discussion, Section 3.4). What seems especially important about the present results, however, is that under normal reading conditions, the eye movement behaviour of young and middle-aged readers was very similar.

The results of the LMEM for effects of age (young vs. middle-aged; middle-aged vs. older) and text contrast are summarised in Table 3.3. For progressive saccade length there were no effects of age or any interactions. For all of the other measures there were no significant interactions between age and stimulus quality for young vs. middle-aged adults, however there were significant interactions between age and stimulus quality for middle-aged vs. older adults. Contrasts comparing the normal and faint text condition were undertaken for each age group. Reducing stimulus quality affected a variety of eye movement measures for all three age groups. For middle-aged and older adults there were longer sentence reading times, longer average fixation durations, fewer skips, more regressions, longer first-pass and rereading times for faint compared to normally presented text (ts> 2). Similarly, for younger adults there were significant effects of stimulus quality for sentence reading times, average fixation durations, first-pass reading time and number of skips (ts> 2.9). However for younger adults there was no effect of stimulus quality for rereading times (β= 12.93, SE= 28.69, t= 0.45) or number of regressive saccades (β= 0.14, SE= 0.08, t= 1.81). Importantly, the significant interactions between middle-aged vs. older adults and stimulus quality reflect the much larger effects of stimulus quality for the older adults compared to the other age groups. In line with the results for the normal reading condition, middle-aged adults demonstrated performance similar to the young adults, with no significant differences. This finding suggests that high stimulus quality is particularly important for the reading of older adults, but this vulnerability to reduced contrast is not yet present in middle-age[5].

[5] For all sentence level comparisons of the young vs. middle-aged group, additional Bayes Factor (BF) analyses were undertaken to confirm the lack of differences between these two age groups. These analyses were computed using the lmBF function within the BayesFactor package (Morey & Rouder, 2015) in R (R Core Team, 2015), with the scaling factor for g-priors set to 0.5, and using 100,000 Monte Carlo iterations. Participants and items were specified as random factors. These analyses favoured a null model with no interaction for these age groups (BFs<1).

	High Contrast	Low Contrast
Sentence reading time(ms)		
Young	2508 (169)	2699 (270)
Middle	2569 (240)	2952 (350)
Older	3040 (240)	4465 (350)
Fixation duration (ms)		
Young	236 (7)	251 (10)
Middle	237 (10)	259 (13)
Older	251 (10)	310 (13)
Progressive saccade length (characters)		
Young	7.9 (0.2)	7.8 (0.2)
Middle	8.5 (0.2)	8.2 (0.2)
Older	8.3 (0.2)	8.0 (0.2)
Number of regressive saccades		
Young	2.4 (0.2)	2.2 (0.2)
Middle	2.3 (0.2)	2.5 (0.3)
Older	3.0 (0.3)	3.5 (0.4)
First-pass reading time (ms)		
Young	1867 (115)	2052 (146)
Middle	1872 (162)	2132 (206)
Older	1970 (163)	2821 (207)
Number of first-pass skips		
Young	5.0 (0.3)	4.7 (0.3)
Middle	5.1 (0.4)	4.7 (0.4)
Older	5.1 (0.4)	4.4 (0.5)
Rereading time (ms)		
Young	530 (113)	543 (171)
Middle	552 (113)	680 (159)
Older	837 (160)	1357 (242)

Table 3.2. Experiment 2, means and standard errors (in parentheses) for sentence level measures.

		Sentence Reading Time (ms)	Fixation Duration (ms)	Progressive Saccade Length (characters)	Number of Regressive Saccades	First-pass Reading Time (ms)	Number of First-Pass Skips	Rereading Time (ms)
Intercept		3041.91	257.35	8.05	2.68	2129.52	4.90	798.05
		118.50	4.61	0.29	0.17	72.67	0.16	74.60
		25.67*	55.46*	27.86*	16.14*	29.31*	52.81*	10.70*
Age								
Middle vs. Older	***β***	1000.40	32.18	0.11	0.73	363.77	0.15	680.77
	SE	284.45	11.24	0.20	0.39	174.72	0.45	178.00
	t	3.52*	2.82*	0.57	1.94	2.08*	0.33	3.32*
Young vs. Middle	***β***	166.66	32.18	0.19	0.16	73.64	0.06	157.96
	SE	284.42	11.24	0.20	0.39	174.72	0.45	178.27
	t	0.58	0.44	0.97	0.41	0.42	0.13	0.89
Contrast								
High vs. Low	***β***	668.38	31.70	0.12	0.20	448.96	0.39	210.10
	SE	84.58	3.29	0.02	0.08	44.35	0.33	53.54
	t	7.92*	9.42*	6.97*	2.42*	10.12*	12.02*	3.92*
Interactions								
Young vs. Middle x Contrast	***β***	194.25	6.32	0.03	0.30	127.84	0.05	68.03
	SE	206.62	8.04	0.04	0.20	108.18	0.08	129.92
	t	0.94	0.79	0.74	1.37	1.18	0.64	0.52
Middle vs. Older x Contrast	***β***	1045.49	38.93	0.06	0.40	535.34	0.36	463.28
	SE	206.79	8.05	0.04	0.20	108.18	0.08	129.80
	t	5.05*	4.84*	1.48	1.98*	4.95*	4.55*	3.60*

Table 3.3. LMEM statistics for sentence-level measures. Significant effects are indicated with an asterisk.

Critical word analyses. Means and standard errors for critical word analyses are shown in Table 3.4. The results of the LMEM for effects of age (young vs. middle-aged; middle-aged vs. older), text contrast and word frequency are summarised in Table 3.5 and graphs displaying key findings are shown in Figures 3.2-3.3. Follow up contrasts to explore interactions are reported in the text. For first-fixation duration, gaze duration and total reading time there were no three-way interactions. However, in line with the results for sentence-level measures, there were significant two-way interactions between age and stimulus quality for middle vs. older, but not for young vs. middle-aged. Follow-up contrasts showed significant effects of stimulus quality for all age groups, with longer first-fixation durations, gaze durations and total times for faint compared to normally presented words (*t*s> 2.9). In line with the sentence-level measures, effects of stimulus quality were larger for the older adults compared to both the younger and middle-aged adults (see Figures below). For first-fixation and gaze duration there were no significant two-way interactions between age group and word frequency, but there was a significant interaction between word frequency and age group for total reading times. In line with the pattern shown in some previous studies, word frequency effects were larger for older adults compared to the other age groups.

For all three reading time measures, there were significant two-way interactions between stimulus quality and word frequency. All three measures were significantly longer for low compared to high frequency words for both faint text and normally presented text (*t*s> 5.20). However, in line with the results of Sheridan and Reingold (2013), the effects were larger for faint text than for normally presented text. Notably, despite interactions between stimulus quality and word frequency, these two-way interactions did not further interact with age group (in all cases *t*< 1.10). Importantly these results indicate that while compared to other age groups the reading of older adults was more disrupted by poor stimulus quality, this was not related to particular difficulties with lexical processing.

In line with the reading time results, word-skipping for young vs. middle-aged adults produced no interactions but clear effects of both word frequency and stimulus quality. That is, in line with previous work, skipping rates were higher for high compared to low frequency words, and for normally-presented compared to faint words. However, for the older adults, in contrast to the reading time measures, word skipping showed a three-way interaction between age (middle-aged vs. older), stimulus quality, and word frequency. For normally-presented text, young and older adults showed significant effects of word frequency so that high frequency words were more likely to be skipped than low frequency words (*t*s >2.00). Middle-aged adults showed the same numerical trend, though this did not reach significance (β= 0.09, SE= 0.07, *t*= 1.76). Crucially, for faint text, although word frequency modulated skipping rates for both young and middle-aged readers (*t*s> 2.00), no significant effects of word frequency were observed for older readers for faint text (β= 0.001, SE= 0.02, *t*= 0.26). This interaction may reflect an inability of older adults to lexically process low-contrast parafoveal text, suggesting that older adults experience particular difficulty processing faint text in the parafovea. This is consistent with the age-group x text contrast interaction in the sentence-level word-skipping analyses.

	High contrast		Low contrast	
	High frequency	Low frequency	High frequency	Low frequency
First-fixation duration (ms)				
Young	215 (7)	234 (8)	232 (12)	260 (14)
Middle	212 (7)	227 (10)	234 (12)	266 (20)
Older	220 (10)	244 (11)	311 (17)	345 (20)
Gaze duration (ms)				
Young	233 (12)	269 (16)	254 (18)	296 (26)
Middle	224 (15)	255 (18)	246 (25)	302 (28)
Older	236 (15)	271 (19)	353 (26)	417 (34)
Total reading time (ms)				
Young	278 (24)	312 (25)	284 (30)	342 (47)
Middle	263 (30)	298 (30)	299 (44)	361 (65)
Older	298 (28)	359 (29)	491 (42)	614 (65)
Proportion of words skipped				
Young	.20 (.04)	.14 (.04)	.17 (.04)	.12 (.04)
Middle	.21 (.04)	.19 (.05)	.21 (.06)	.14 (.06)
Older	.23 (.06)	.18 (.06)	.15 (.06)	.16 (.06)

Table 3.4. Experiment 2, means and standard errors (in parentheses) for critical word measures.

		First-Fixation Duration (ms)	Gaze Duration (ms)	Total Reading Time (ms)	Proportion of words skipped
Intercept		251.74	279.31	340.70	1.89
		5.79	8.12	15.91	0.16
		43.46	34.41*	21.98	11.52*
Age					
Middle vs. Older	***β***	49.96	61.96	143.43	0.02
	SE	12.88	18.24	35.15	0.05
	t/z	3.64*	3.40*	4.08*	0.37
Young vs. Middle	***β***	2.13	4.88	0.22	0.04
	SE	12.88	18.22	35.15	0.05
	t/z	0.17	0.27	0.01	0.74
Frequency					
High vs. Low Frequency	***β***	26.13	46.20	68.89	0.05
	SE	2.18	3.39	5.38	0.01
	t/z	11.99*	13.61*	12.80*	5.36*
Contrast					
High vs. low	***β***	0.35	64.40	99.93	0.03
	SE	0.08	7.46	14.55	0.01
	t/z	10.34*	8.63*	6.87*	2.74*
Age x Frequency					
Young vs. Middle x Frequency	***β***	0.47	4.23	3.30	0.01
	SE	5.37	8.32	13.27	0.02
	t/z	0.09	0.51	0.25	0.08
Middle vs. Older x Frequency	***β***	5.21	13.82	57.99	0.04
	SE	5.34	8.36	13.21	0.02
	t/z	0.98	1.65	4.39*	1.73
Age x Contrast					
Young vs. Middle x Contrast	***β***	9.20	11.09	30.57	0.01
	SE	11.61	17.74	35.32	0.02
	t/z	0.79	0.63	0.87	0.55
Middle vs. Older x Contrast	***β***	65.31	99.57	184.99	0.04
	SE	11.60	17.79	35.30	0.02
	t/z	5.63*	5.60*	5.24*	1.49
Contrast x Frequency					
Contrast x Frequency	***β***	11.53	22.53	55.75	0.01
	SE	4.36	6.79	10.77	0.02
	t/z	2.64*	3.32*	5.18*	0.07
Age x Contrast x Frequency					
Young vs. Middle x Contrast x Frequency	***β***	6.69	15.17	3.60	0.11
	SE	10.75	16.64	26.55	0.05
	t/z	0.62	0.91	0.14	1.44
Middle vs. Older x Contrast x Frequency	***β***	5.95	12.81	40.99	0.14
	SE	10.69	16.75	26.44	0.05
	t/z	0.56	0.76	1.06	3.15*

Table 3.5. Experiment 1, LMEM statistics for critical word measures. Significant effects are indicated with an asterisk.

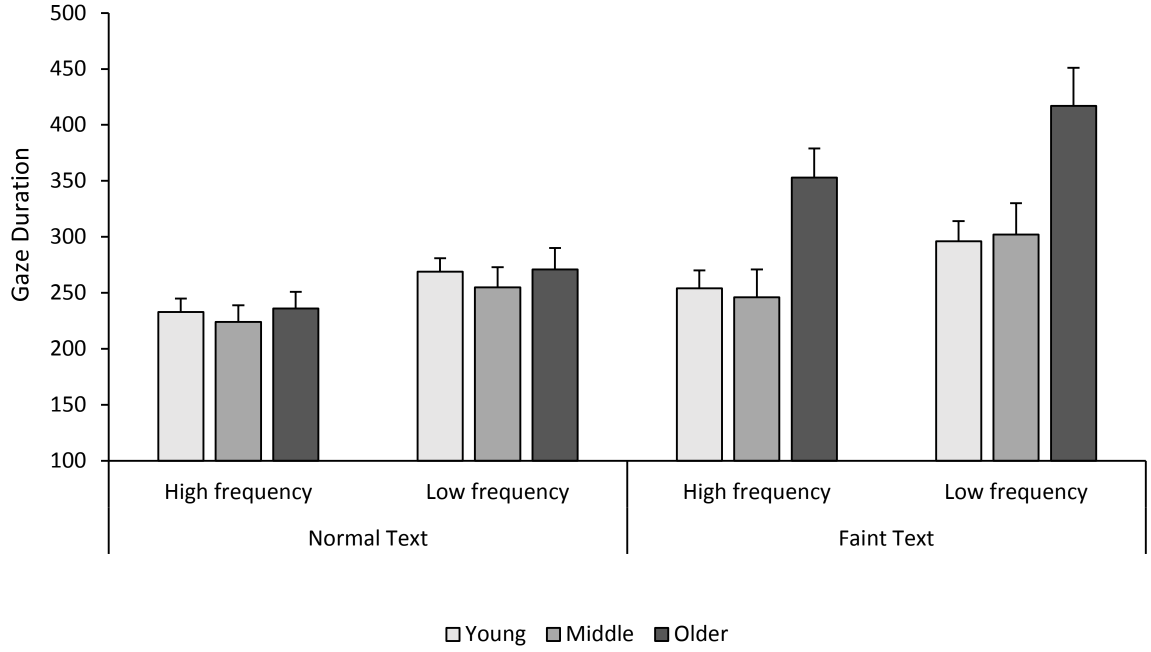

Figure 3.2. Experiment 2. Mean gaze duration (ms). Error bars correspond to the standard error.

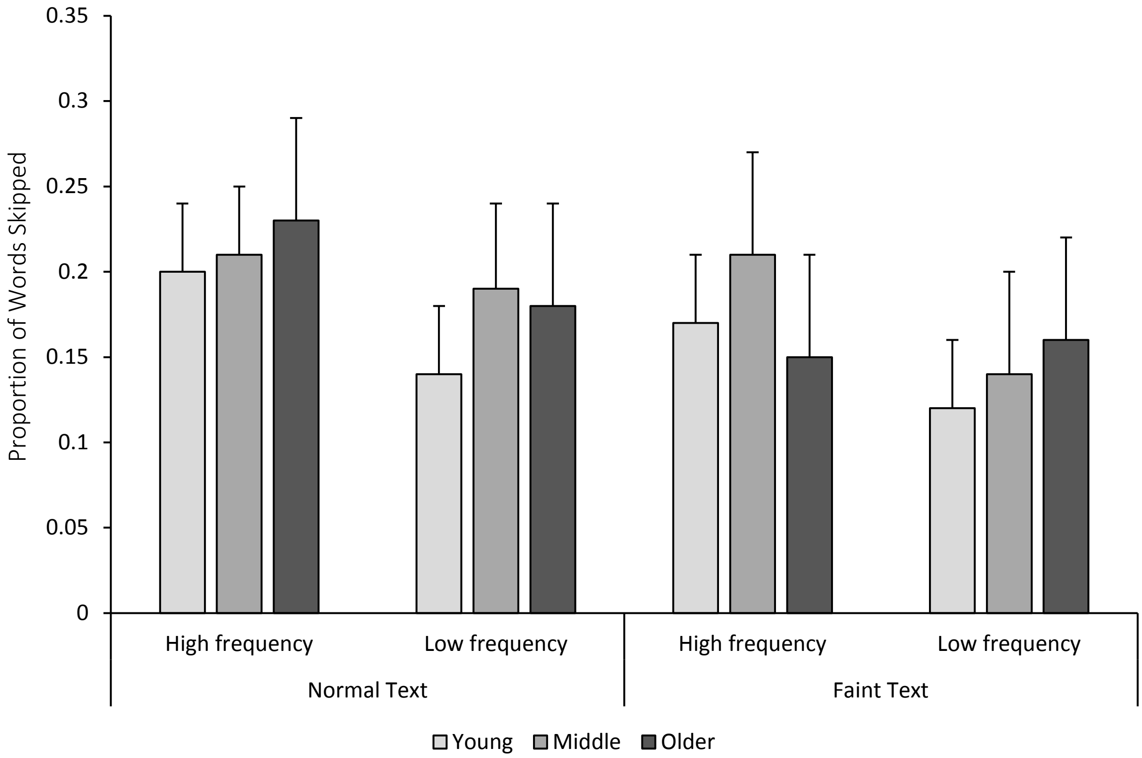

Figure 3.3. Experiment 2. Mean proportion of words skipped. Error bars correspond to the standard error.

3.2.3 Discussion

Experiment 2 shows clear adult age differences in reading for participants aged 65+. These effects are consistent with those of previous studies (e.g. Rayner et al., 2006, see also Appendix A). Older adults produced longer sentence reading times, and more regressive saccades than both young and middle-aged adults. These differences in reading performance suggest that the older adults were experiencing greater reading difficulty. Crucially, these adult age differences were not seen in the middle-aged group, who showed broadly similar eye movement behaviour to the young adults. This study provides an important indication that that reading processes and eye movement control are likely similar for middle-aged and young adults. This is in contrast to some previous research (Soederberg Miller, 2009, Calabrèse et al., 2016; see also, Teramoto et al, 2012).

Reducing text contrast affected a variety of eye movement measures, during both first-pass and rereading. These effects are in line with previous studies with young adults which have examined the effects of reduced contrast for entire sentences (Hohenstein & Kliegl, 2014; Liu et al., 2015; Jainta et al., 2017; White & Staub, 2012). Also in line with previous research, words in the faint text condition were less likely to be skipped than normally presented words (Drieghe, 2008; Hohenstein & Kliegl, 2014; Sheridan & Reingold, 2013). Importantly, older readers experienced greater disruption resulting from reduced contrast than both young and middle-aged readers. This was found across a variety of eye movement measures and builds on previous research demonstrating greater increases in reading time (Mitzner & Rogers, 2006) and suggests that older adults are particularly vulnerable to the effects of low-contrast text. Crucially, these additional difficulties in reading low-contrast text were not seen in the middle-aged participants. This suggests that despite the onset of neural and optical changes occurring in middle-age (Schefrin et al., 1999; Owsley, 2011) the reading difficulties associated with advanced age do not affect reading behaviour for middle-aged adults.

A main effect of word frequency was found across all measures. Frequency also interacted with contrast for reading time measures. This interaction emerged early, from the duration of the first-fixation, and was present throughout the reading process. This finding provides support for the notion that stimulus quality has an early influence on lexical processing. Therefore, this suggests that when contrast is reduced, word identification is made more difficult. This is in line with results from single word recognition studies which have found interactive effects of stimulus quality and word frequency in semantic categorisation and pronunciation tasks (O'Malley et al., 2007; Yap & Balota, 2007). This is also consistent with the results of Sheridan and Reingold (2013) who used faint critical words embedded within sentences to examine effects of stimulus quality and word frequency in natural reading. However, these findings differ from the additive effects shown in LDT (Balota & Abrams, 1995; Becker & Killion, 1977; Plourde & Besner, 1997; Stanners et al, 1975; Yap & Balota, 2007) and also for entire-sentence manipulations of stimulus quality (Lui et al, 2015; Jainta et al., 2017). The potential role of task and orthography differences will be discussed further in the General Discussion (Section 3.4). Crucially, the influence of reduced contrast on word identification on reading times was similar for the three age-groups. However, the interaction between age, contrast and word frequency found in word skipping suggests that older adults may struggle to parafoveally process faint text, and this may be a source of difficulty. Overall, these findings provide an important indication that, while overall, compared to other age groups, the reading of older adults was more disrupted by reducing text contrast, this was not due to additional difficulties with lexical processing. Experiment 3 builds on this work by examining the effect of text contrast for parafoveal text.

3.3 Experiment 3

Experiment 2 demonstrated that older adults' reading is less resilient to changes in stimulus quality than young and middle-aged readers. Building on these findings, Experiment 3 investigated the effects of reduced text contrast on parafoveal processing by presenting text to the right of each fixated word either normally or with contrast reduced. Experiment 2, and most previous studies examining effects of stimulus quality on reading behaviour, manipulated the stimulus quality for words prior to, during, and after fixation (that is, both in the fovea and parafovea). However, few studies have specifically examined how text contrast modulates processing of fixated words (Glaholt et al., 2014) and parafoveal words (Hohenstein & Kliegl, 2014; see also: Wang & Inhoff, 2010). Using a variant of the Yang and McConkie (2001, 2004) single fixation replacement paradigm to reduce text contrast only during individual fixations, Glaholt et al (2014) found that stimulus quality had an immediate effect on fixation durations even when the reduction in stimulus quality was not predictable and could not be parafoveally previewed. This suggests that contrast does modulate the processing of fixated words. Hohenstein and Kliegl (2014) used the gaze-contingent boundary technique with a between-participants design to compare young adults reading times on words with accurate and inaccurate previews. This study found no effect of stimulus quality on parafoveal preview benefit. However, there was also no effect of stimulus quality on critical word reading times (this study also used German capitalised nouns as critical words- an issue considered in the General Discussion, Section 3.4).

Visual contrast is known to affect recognition of stimuli outside of central vision (Strasburger, Rentschler, & Jüttner, 2011), and parafoveal processing is known to be a crucial component of skilled reading (see Schotter, Angele, & Rayner, 2012). Reducing text contrast may be particularly disruptive to parafoveal processing of upcoming words for older readers. Many of the changes in visual abilities that occur during the normal ageing process are greatest outside of central vision, including age-related declines in visual acuity, contrast sensitivity (described in Chapter 1, Section 1.2.1 Crassini et al., 1988; Gillespie-Gallery, Konstantakopoulou, Harlow, & Barbur, 2013) and visual crowding (McCarley, Yamani, Kramer, & Mounts, 2012; Scialfa, Cordazzo, Bubric, & Lyon, 2013). Therefore, Experiment 3 provides a test of the role of stimulus quality in parafoveal processing during natural reading for both young and older readers. As little difference was observed between young and middle-aged adults in Experiment 2, Experiment 3 focused only on young and older adult readers.

Experiment 3 employed a variation of the gaze-contingent text change technique (McConkie & Rayner, 1975) to present upcoming words in the parafovea in low-contrast (Figure in methods section). The fixated word, and all previously encountered words, were presented normally in high-contrast, while upcoming text was presented in low-contrast and so appeared faint. The current manipulation bears some similarity to other gaze-contingent methods (Marx, Hawelka, Schuster, & Hutzler, 2015; Marx, Hutzler, Schuster & Hawelka, 2016; Rayner, Yang, Schuett, & Slattery, 2014). However, one crucial difference is that the current manipulation was employed only for first-pass reading; all words to the left of fixation were presented normally and remained high-contrast during rereading.

This study aimed to examine whether young and older readers are differentially affected by a reduction in text contrast in the parafovea. Given the changes in visual abilities that occur with advancing age, it is anticipated that young adults will be better able to use low-contrast parafoveal text for saccade programming. Therefore, in the present study it is predicted that younger readers will be able to extract more useful information than older adults from low-contrast upcoming text and therefore the reading of older adults will be disrupted more by the presence of faint text in the parafovea to the right of fixation. As upcoming text was always orthographically correct, the pattern of predicted age differences is different to that for studies that assess preview benefit by comparing correct and incorrect orthographic previews (See Chapter 1, Section 1.5.1 for a description of this paradigm, e.g. Rayner, Castelhano & Yang, 2010). In preview benefit studies, neither age group can extract useful information from an incorrect preview, and young adults can benefit more from the correct preview, hence the preview effect is larger (more benefit) for young adults. In contrast, in the present study it is predicted that young adult readers extract more useful information than older adults from low-contrast upcoming text, hence the effect of this manipulation is predicted to be larger (and so more detrimental) for older adults. Note that for consistency with Experiment 2 a word frequency manipulation is included in Experiment 3. However, as fixated words are always presented at high-contrast in Experiment 3, it was not anticipated that stimulus quality would modulate the size of the word frequency effect for reading times measures.

3.3.1 Method

Participants. Sixteen young adults (*M*= 20.1, range= 18-24, 11 female) and 16 older adults (*M*= 20.1, range= 18-24, 10 female) were recruited from the University of Leicester and the surrounding community. None took part in Experiment 2. Criteria for participating were the same as in Experiment 1 and 2 and participants' visual abilities were assessed using the same tests, these details are summarised in Table 3.6. Older adults had poorer visual acuity at computer distance and poorer contrast sensitivity in comparison to the young adults (*p*s <.05). Participants were well matched on years of education and reading activity (*p*s >.05). Three older adults were excluded due to an inability to read foveally presented low-contrast text. One young adult was excluded due to tracking difficulty.

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/17	20/14-20/22	20/25	20/16-20/36
Low contrast near acuity	20/28	20/20-20/35	20/40	20/23-20/53
High contrast distance acuity	20/18	20/16-20/25	20/25	20/17-20/32
Low contrast distance acuity	20/28	20/22-20/35	20/36	20/25-20/53
Screen distance acuity	20/18	20/16-20/25	20/24	20/18-20/32
Contrast-sensitivity	2.00	1.95-2.10	1.95	1.95-2.00
Years of education	14.5	17-18	13.7	11-20
Hours spent reading/week	12.1	4-30	12.8	5-25

Table 3.6. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 3. Appropriate correction was applied to calculate acuity at the distances used.

Materials and design. The same materials and Latin square design were employed as in Experiment 2. In the faint condition upcoming text was presented at low-contrast during first-pass reading (Figure 3.4). A boundary was placed between every word, so that each word was always presented at high-contrast at the point of fixation, and upcoming text was presented at low-contrast. This manipulation was employed only during first-pass reading. Therefore, once each boundary was crossed the word remained at high-contrast (including during rereading).

Apparatus. The apparatus was the same as in previous experiments.

Procedure & Analyses. The general procedure, measures and analyses were the same as for Experiment 2. 1.2% of fixations were discarded due to being shorter than 80ms or longer than 1,200ms. All participants achieved a high level of comprehension accuracy in all conditions the experiment (at least 85%).

```
                    *
He knew that the small room would be really useful for storage.

                         *
He knew that the small room would be really useful for storage.

                              *
He knew that the small room would be really useful for storage.

                        *
He knew that the small room would be really useful for storage.
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Figure 3.4. Experiment 3. A demonstration of the gaze-contingent change in the low-contrast upcoming text condition. The asterisk represents the point of fixation. Once an invisible boundary is crossed before each word, the word changes to high-contrast, this word remains high-contrast if a regression is made.

3.3.2 Results

Sentence-level analyses. Means and standard errors for sentence level analyses are shown in Table 3.7. Adult age differences in line with Experiment 2 were found for normally presented text. Older adults produced longer reading (β= 442.10, *SE*= 213.50, *t*= 2.07), and fixation times (β= 19.04, *SE*= 8.83, *t*= 2.16), made longer progressive saccades (β= 0.51, *SE*= 0.17, *t*= 3.15), more regressive saccades (β= 1.10, *SE*=0.90, *t*= 2.30) and spent more time rereading (β= 74.17, *SE*= 27.64, *t*= 2.68) than young adults. No significant age effects were found for number of first-pass skips or first-pass reading times (all *t*s <1.20). Accordingly, while the older adults read more slowly than the young adults, differences in word-skipping were not observed across the two age-groups. As in Experiment 2, these findings are broadly in line with previous research (e.g. Rayner et al., 2006) but, similar to Experiment 2, did not show significant age differences in word-skipping, this is also in contrast to Experiment 1, see Appendix A, see also General Discussion, Section 3.4).

The results of the LMEM for effects of age (young vs. older) and text contrast are summarised in Table 3.8. There were significant effects of age group for measures sensitive to rereading behaviour (number of regressive saccades and rereading time). For these measures, there were no effects of upcoming text contrast and no interactions. Therefore, when stimulus quality is manipulated both foveally and parafoveally (Experiment 2) text contrast modulated rereading behaviour, but when stimulus quality was only manipulated for upcoming words to the right of fixation (Experiment 3) there was no effect of text contrast on rereading behaviour.

In contrast to measures sensitive to rereading, all other sentence-level measures produced significant interactions between age and upcoming text stimulus quality, such that effects of stimulus quality were larger for older than younger adults. Both groups produced significantly longer sentence reading times, fixation durations, and first-pass reading times, significantly fewer first-pass skips, and significantly shorter progressive saccade lengths in the faint compared to the normal upcoming text condition (*t*s > 2.4), but these effects were larger for the older adults. Overall, the sentence-level results suggest both age groups benefit from the availability of high visual quality text in the parafovea. However, in line with predictions, older adults appear to have greater difficulty in processing parafoveal text when it is presented in low-contrast.

Measure	Normal Upcoming Text	Faint Upcoming Text
Sentence reading time (ms)		
Young	2344 (170)	2481 (250)
Older	2800 (280)	3406 (350)
Fixation duration (ms)		
Young	212 (6)	222 (6)
Older	232 (7)	252 (7)
Progressive saccade length (characters)		
Young	7.3 (0.1)	7.0 (0.1)
Older	8.9 (0.1)	7.9 (0.1)
Number of regressive saccades		
Young	2.1 (0.2)	2.1 (0.2)
Older	3.0 (0.2)	3.1 (0.2)
First-pass reading time (ms)		
Young	1940 (106)	2065 (109)
Older	2067 (150)	2606 (154)
Number of first-pass skips		
Young	4.5 (0.3)	4.1 (0.3)
Older	4.9 (0.3)	4.0 (0.3)
Rereading time (ms)		
Young	468 (61)	468 (64)
Older	638 (86)	683 (91)

Table 3.7. Experiment 3, means and standard errors (in parentheses) for sentence level measures.

		Sentence Reading Time (ms)	Fixation Duration (ms)	Progressive Saccade Length (characters)	Number of regressive saccades	First pass Reading Time (ms)	Number of First Pass Skips	Rereading Time (ms)
Intercept	***β***	2751.70	229.19	7.79	2.46	1966.66	4.42	720.14
	SE	109.09	4.45	0.25	0.17	75.61	0.20	86.85
	t	25.22*	51.54*	31.49*	14.80*	26.01*	22.66*	8.29*
Age	***β***	669.99	25.56	0.12	0.25	321.29	0.20	99.66
	SE	208.29	8.63	0.49	0.11	148.03	0.20	38.30
	t	3.36*	2.96*	0.25	2.48*	2.17*	0.49	2.78*
Upcoming text contrast	***β***	358.09	13.72	0.76	0.01	337.52	0.60	2.36
	SE	38.82	1.65	0.09	0.04	29.48	0.30	11.35
	t	9.22*	8.30*	8.65*	0.07	11.45*	8.42*	0.10
Age x Upcoming text contrast	***β***	471.14	10.68	0.86	0.04	418.59	0.60	21.94
	SE	77.62	3.31	0.17	0.08	58.97	0.10	22.20
	t	6.07*	3.23*	4.90*	0.52	7.10*	4.74*	1.13

Table 3.8. LMEM statistics for sentence-level measures. Significant effects are indicated with an asterisk.

Critical word analyses. Means and standard errors for the critical word analyses are shown in Table 3.9. The results of the LMEM for effects of age (young vs. middle-aged; middle-aged vs. older), text contrast and word frequency are summarised in Table 3.10, and graphs showing key measures are shown in Figure 3.5-3.6. Follow up contrasts are reported in the text. There were significant effects of age and upcoming text contrast for all three reading time measures for the critical word, and significant interactions between these factors. For first-fixation duration and gaze duration, there were significant effects of upcoming text contrast for older (first fixation duration; β=21.04, *SE*= 4.05, *t*= 5.20, gaze duration; β=27.37, *SE*= 4.12, *t*= 6.64) but not younger (first fixation duration; β= 2.99, *SE*= 4.08, *t*= 0.73, gaze duration; β= 5.75, *SE*= 4.02, *t*= 1.43) adults. Both groups produced significantly longer total times for faint compared to normal upcoming text (*t*s > 1.96). The interaction reflects a larger effect for older compared to young adults. In line with the sentence-level measures, these results indicate that both age groups benefit from high-contrast parafoveal text but older adults have particular difficulty processing low-contrast parafoveal text.

In line with Experiment 2 and previous studies, there were significantly longer reading times for low- compared to high-frequency words (demonstrated in Figure 3.5). There were no significant interactions between word frequency and age (though first fixation durations and total times did show a numerically larger frequency effect for older readers). In contrast to Experiment 2, the results for reading times on the critical word showed no interaction between word frequency and upcoming text contrast, indicating that the interactive pattern in Experiment 2 reflects foveal processing of the critical word rather than an effect of the stimulus quality of parafoveal text. There were also no three-way interactions for any reading time measures. Therefore, having the foveal word presented intact appears to support normal lexical processing for both age groups even when the contrast of text in the parafovea is low.

For word skipping, there was a significant effect of word frequency and a significant interaction between age-group and upcoming text contrast. The interaction was such that, when collapsed across the word frequency conditions, young adults, but not older adults, appeared to have higher skipping rates when upcoming text was presented at low-contrast. However, this pattern must be interpreted with caution as it contrasts with the pattern of word-skipping effects in the sentence-level analyses for this experiment, and also the word-skipping effects observed in Experiment 2. Recall that in Experiment 2 there was a significant effect of stimulus quality on word skipping that was qualified by a three-way interaction, such that young readers showed effects of word frequency on word skipping regardless of stimulus quality, whereas word frequency only modulated word skipping for normally-presented text for older readers. In contrast, for Experiment 3 there was no significant three-way interaction. However, for both groups, word frequency effects were numerically smaller for low- compared to high-contrast upcoming text, though the interaction between word frequency and stimulus quality did not reach significance (t= 1.78).

	High contrast upcoming text		Low contrast upcoming text	
	High Frequency	Low Frequency	High Frequency	Low Frequency
First-fixation duration (ms)				
Young	201(6)	217(9)	205(7)	219(9)
Older	228(9)	255(12)	251(11)	273(13)
Gaze duration (ms)				
Young	212(9)	252(14)	222(9)	248(17)
Older	239(12)	281(20)	272(13)	309(24)
Total reading time (ms)				
Young	241(14)	291(23)	249(17)	295(27)
Older	301(20)	366(32)	332(24)	401(38)
Proportion of words skipped				
Young	.20(.03)	.14(.03)	.23(.04)	.22(.04)
Older	.23(.05)	.17(.05)	.18(.05)	.17(.04)

Table 3.9. Experiment 3, means and standard errors (in parentheses) for critical word measures.

		First-fixation duration (ms)	Gaze Duration (ms)	Total Reading Time (ms)	Proportion of words skipped
Intercept	***β***	230.21	250.73	306.03	1.75
	SE	5.34	7.94	11.96	0.17
	t/z	43.14*	31.71*	25.59*	10.07*
Age	***β***	39.75	44.08	81.34	0.14
	SE	10.46	15.68	22.96	0.33
	t/z	3.80*	2.81*	3.54*	0.43
Frequency	***β***	19.82	36.68	58.30	0.43
	SE	2.37	3.18	5.48	0.13
	t/z	8.37*	11.55*	10.64*	3.30*
Upcoming text contrast	***β***	12.49	16.91	19.00	0.12
	SE	2.37	3.18	5.48	0.20
	t/z	5.28*	5.33*	3.47*	0.95
Age x Frequency	***β***	8.47	6.52	17.68	0.10
	SE	4.73	6.35	10.96	0.23
	t/z	1.79	1.03	1.61	0.48
Age x contrast	***β***	18.52	31.31	27.86	0.67
	SE	4.73	6.35	10.96	0.23
	t/z	3.91*	4.93*	2.54*	2.93*
Contrast x Frequency	***β***	4.06	9.41	0.62	0.40
	SE	4.73	6.35	10.96	0.23
	t/z	0.86	1.48	0.06	1.78
Age x Contrast x Frequency	***β***	4.74	9.40	9.15	0.19
	SE	9.47	12.70	21.91	0.38
	t/z	0.50	0.74	0.41	0.48

Table 3.10. LMEM statistics for critical word measures. Significant effects are indicated with an asterisk.

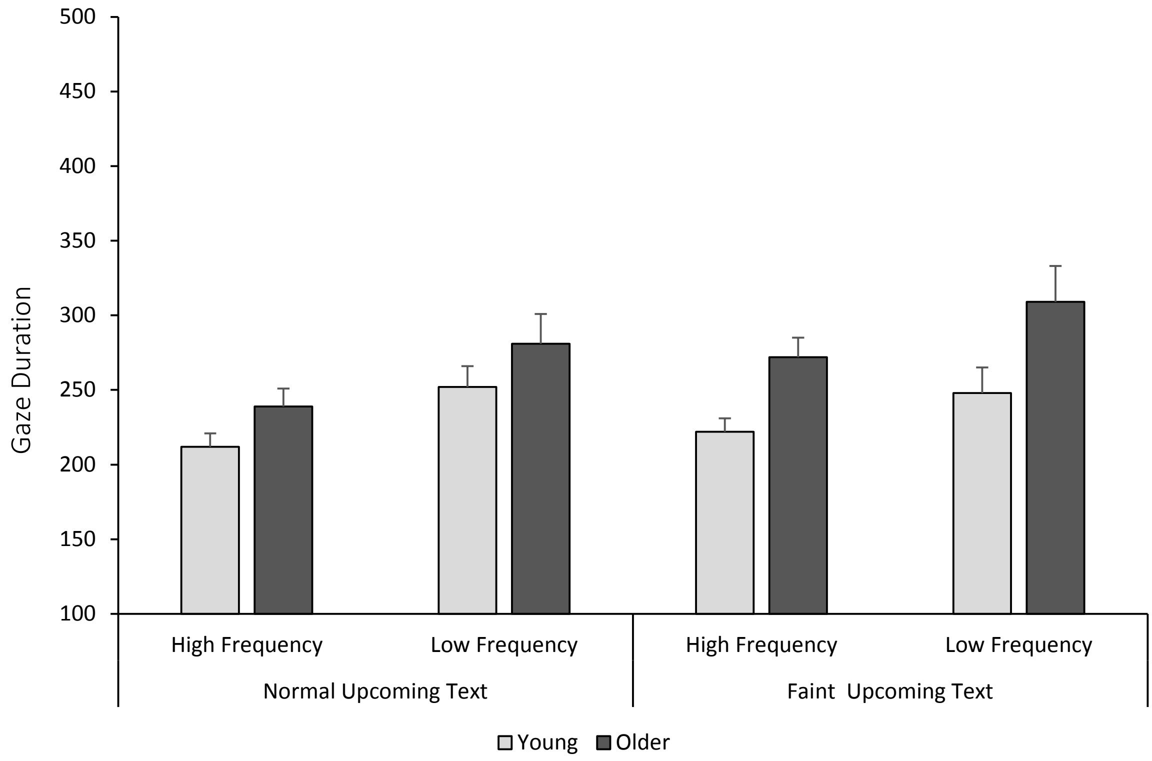

Figure 3.5. Experiment 3. Mean gaze duration (ms). Error bars correspond to the standard error.

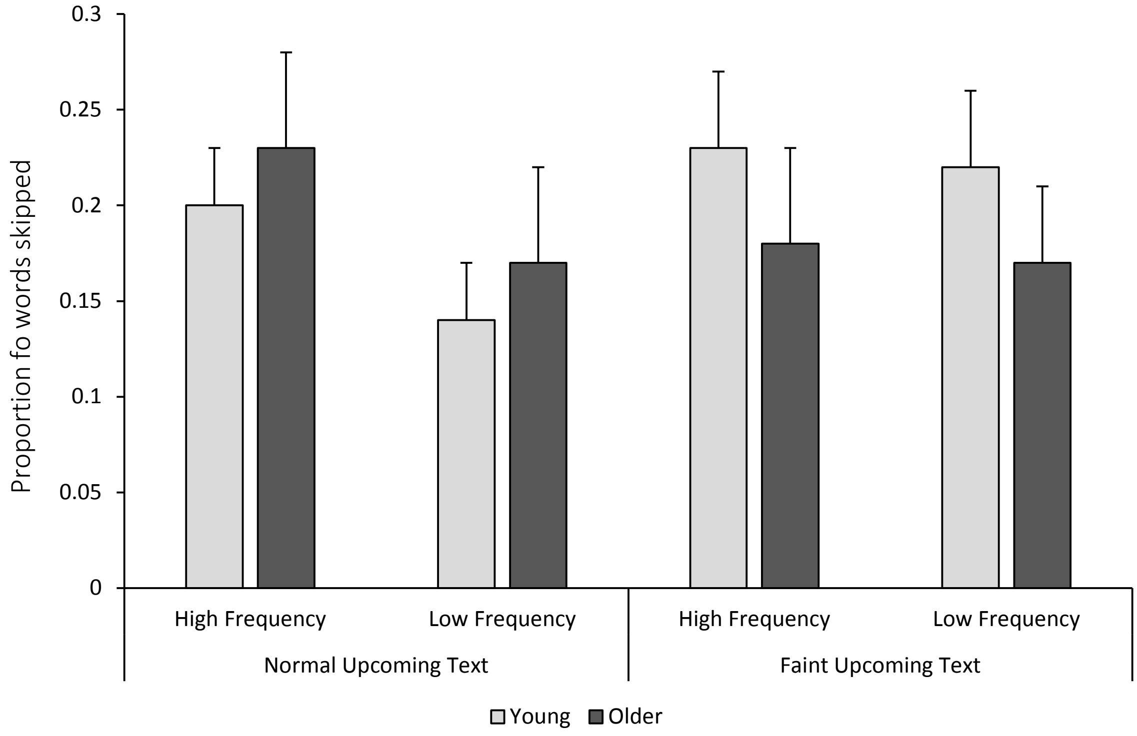

Figure 3.6. Experiment 3. Mean proportion of words skipped. Error bars correspond to the standard error.

3.3.3 Discussion

As in Experiment 2, adult age differences in reading in line with previous studies were found with older adults showing longer sentence reading times and more regressive saccades than young adults (see also, Appendix A). This further demonstrates that older adults are experiencing reading difficulty (e.g. Rayner et al., 2006). Effects of upcoming text contrast were also found for both age groups in the sentence-level analyses, suggesting that both groups benefitted from the availability of high-contrast text in the parafovea. These results build on previous findings (Hohenstein & Kliegl, 2014) suggesting that the contrast of upcoming text contributes to the reading difficulties shown when reading text presented entirely at low-contrast (both foveally and parafoveally) (e.g. Reingold & Rayner, 2006; White & Staub, 2012). The effects of upcoming text contrast on reading times are likely due to parafoveal preprocessing (that is, the influence of parafoveal text on word skipping probabilities and subsequent reading times)[6]. However note that effects could also arise due to parafoveal-on-foveal effects (that is, the influence of parafoveal text characteristics on reading behaviour for preceding words, rather than an effect on the subsequent foveal processing of the parafoveal word) (see Kennedy & Pynte, 2005).

Crucially, older adults showed greater increases in reading time than young adults when text presented in the parafovea was faint. This suggests that older adults experience greater difficulty than young adults in processing parafoveal information in the absence of a high-contrast preview. It is important to note that the current manipulation is different to standard preview studies, which typically show smaller preview benefit for older adults (Rayner, Castelhano & Yang, 2010) because readers have the potential to also benefit from the low-contrast preview. For the young adults, superior visual abilities may enable them to extract more information from low-contrast previews compared to older adults.

Interestingly, effects of word frequency and upcoming text contrast produced additive effects for critical word reading times. It appears that when the foveal word is presented normally, lexical processing of fixated words is not modulated by upcoming

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[6] Note that the contrast of stimuli in the parafovea has been shown to modulate processing of the fixated stimulus (Levitt & Lund, 1997; Xing & Heeger, 2000).

text contrast. The parafoveal preview is likely to be especially important in the very early stages of word recognition, and it may be that the processes underlying the interactive pattern in Experiment 2 occur primarily during the foveal, rather than parafoveal, processing of words. The additive effects of word frequency and upcoming text contrast for both young and older adults are especially striking given that previous studies show smaller or delayed effects of word frequency when accurate previews of the critical word are denied (Inhoff & Rayner, 1986; Rayner, Liversedge & White, 2006; Reingold, Reichle, Glaholt, & Sheridan, 2012). In contrast, in the present study, although low-contrast previews resulted in longer reading times, there was no apparent detriment to lexical processing. However future studies may employ distributional analyses to further examine whether the stimulus quality of upcoming text modulates the time course of lexical influences on fixation durations (see Reingold et al., 2012), with potentially important implications for theoretical models of the underlying mechanisms (Sheridan & Reichle, 2016).

3.4 General Discussion

In the current study text contrast was manipulated to explore the impact of reading faint text on the eye movement behaviour of different age groups. This study yielded three key novel findings: (1) Adult age differences in reading normal (high-contrast) text: In addition to effects of older age in line with previous studies, Experiment 2 further demonstrated that the reading behaviour of middle-aged readers is comparable to that of younger adults. (2) Effects of text contrast: Eye movement behaviour of older readers is substantially more disrupted by faint (low-contrast) text presentation compared to younger readers, both for text presented entirely in low-contrast (Experiment 2) and for parafoveal modulations of text contrast (Experiment 3). (3) Stimulus quality and lexical processing: In line with Sheridan and Reingold (2013) Experiment 2 demonstrated an interactive effect of stimulus quality and word frequency, crucially the same pattern is shown to hold for older readers. Overall, although older adults do show substantially more disruption from low-contrast text presentations, this difficulty appears to impact largely at a visual level of text processing, with no particular disruption at the lexical level. Together, these two experiments presented here provide important insights in to the effects of reduced stimulus quality both foveally and parafoveally on reading across the lifespan. Each of these key findings are discussed in turn.

Adult age differences in reading normal (high-contrast) text

In line with previous studies, the experiments reported here clearly show that older adults (aged 65+ years) experience greater reading difficulty than young adults (aged 18-24 years). Even when reading normally presented text, the older adults read more slowly and made longer fixations and more regressive saccades than young readers. The broad pattern of this age-related reading difficulty is similar to that reported previously (e.g. Kliegl et al., 2004; McGowan et al., 2014; McGowan et al., 2015; Paterson et al., 2013a; Rayner et al., 2006; Rayner et al., 2009; Stine-Morrow et al., 2010, see also Appendix A). The results of Experiment 2 also provided some indication that older adults produce larger word frequency effects than young adults by producing disproportionately longer reading times on infrequent words (Kliegl et al., 2004; McGowan et al., 2015; Rayner et al., 2006, 2013), although this pattern did not reach significance in Experiment 3. Unlike in many previous experiments, (Kliegl et al., 2004; McGowan et al., 2014, 2015; Rayner et al. 2006; but see Choi et al., 2017; Whitford & Titone, 2016, 2017), older adults did not skip more than young adults. It is argued in the next section that the tendency for older adults to skip words more often may be lessened in more difficult reading conditions (see Wotschack & Kliegl, 2013, see also, Chapter 6, Section 6.2.4).

Crucially, Experiment 2 was among the first to compare the eye movement behaviour of middle-aged readers (aged 40-51 years) to young and older readers. Previous studies have hinted at age differences in reading for those in middle-age (Soederberg Miller, 2009, Calabrèse et al., 2016; see also, Teramoto et al, 2012), however the maximum age of participants in these studies (59 years) was higher than that for the middle-aged participants included here (51 years). The results of Experiment 2 provide a promising initial indication that age related declines in reading performance are not yet present for middle-aged readers (at least within the range of 41 to 51 years), despite the onset of neural and optical changes beginning at around 40 years of age (Schefrin et al., 1999; Owsley, 2011).

Effects of text contrast

In line with Mitzner and Rogers (2006) the present study shows larger effects of text contrast on reading times for older adults. Building on this work, Experiment 2 was the first study to employ eye movement measures to examine this difference in detail. Experiment 2 showed that reducing the contrast of all words within a sentence disrupts normal eye movement behaviour more for older, than for young readers or middle-aged readers, who showed similar performance to young adult readers. Experiment 3 additionally found that reducing the contrast of all upcoming words within a sentence disrupts normal eye movement behaviour more for older, than for young readers. Additionally, in both experiments older readers were less likely to skip words in the faint text condition. These results indicate that older adults are less able to make use of low-contrast text in the parafovea. The indication, therefore, is that the reading performance of older adults is especially vulnerable to reductions in stimulus quality both in the fovea and in the parafovea[7]. This pattern was found consistently across a number of reading times measures. In addition, while the pattern of results for word skipping on the critical word was more complex, there are some key similarities between the two experiments. In both, older adults reduced their skipping in the faint text condition more than young adults. This was seen in sentence-level analyses in Experiment 2 and in both sentence level and critical word analyses in Experiment 3. Together the results are consistent with previous research showing that older adults skip less in more difficult reading conditions (see Wotschack & Kliegl, 2013). Given the intermingling of the normal and faint sentences, older adults' expectation that they may encounter faint text may have resulted in a more cautious reading strategy throughout the experiment, for both the normal and the faint sentences. That is, the increased difficulty associated with the low-contrast text presentations may have prompted older adults in the present experiments to adopt a more careful reading strategy than in previous studies (e.g., Rayner et al., 2006, see also Chapter 6, Section 6.2.4).

The numerous visual declines that occur in older age are likely to be a key component in this differential response to reduced stimulus quality. In particular, older age results in a gradual loss of sensitivity to fine visual detail so that higher contrast is often required (Owsley, 2011). This may be an important component of the reading difficulty that older adults experience. It will be important for future development of models of eye movement control during reading (e.g. Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003) to consider this differential response to manipulations of the physical properties of text across the lifespan (discussed further in the next section).

Stimulus quality and lexical processing

A further concern was to establish if a reduction in stimulus quality affects only the early encoding of visual features or also the subsequent lexical processing of words. The answer has implications for understanding word recognition processes and eye movement control mechanisms. The results of recent studies on effects of text contrast

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[7] The magnitude of the contrast reduction may not be equal across age groups. Further research may explore this possibility by equating contrast in the baseline (high-contrast) condition across the age groups (or for individuals) depending on contrast acuity.

and word frequency for young adults have been inconsistent. The results in the present study are consistent with previous studies for which the stimulus quality of only a single critical word in the sentence was manipulated. Such studies have shown an interactive pattern of results, with larger effects of word frequency in early eye movement measures for words presented at low-contrast, consistent with an early influence of stimulus quality on lexical processing (Liu et al., 2015; Sheridan & Reingold, 2013). However, experiments that manipulated the stimulus quality of the entire sentence have instead shown additive effects of the two variables (Jainta et al., 2016; Liu et al., 2015), in line with an effect of stimulus quality at visual stages of processing (e.g. feature extraction), but not lexical stages. These additive results contrast with the interactive pattern shown here.

Liu et al.'s study employed Chinese text. It is currently unclear within sentence reading experiments whether language (Chinese/English) or display format (single faint word/fully faint sentence) are responsible for the differences between Liu et al.'s study and Experiment 2. Liu et al. (2015) suggest that, for an unspaced language such as Chinese, word segmentation becomes much more difficult when stimulus quality is reduced, in addition characters in logographic orthographies are considerably more complex than alphabetic characters. This may be a crucial difference between the processing of degraded text in English and in Chinese. However, Liu et al. also employed a very low-contrast stimulus quality manipulation, therefore either or both of these factors could have contributed to a different pattern of results. However, differences in results between the present study and those of Jainta et al. point to the possibility that even relatively subtle differences in orthography might modulate effects of stimulus quality. Jainta et al.'s (2016) study employed German text, for which critical words could be capitalised (as standard for German nouns). Capitalisation has been shown to influence how words are processed, perhaps due to the visual salience of the initial letter (Hohenstein & Kliegl, 2013; Rayner & Schotter, 2014). In Experiment 2 contrast influenced all three reading time measures on the critical word. In contrast in Jainta et al.'s study, which employed a similar contrast manipulation, text contrast influenced only first-fixation durations and not gaze durations or total time. It could be that the visually salient capitalisation cues in Jainta et al.'s study facilitated orthographic processing of these words, mitigating the effects of the low-contrast presentation format. The interaction between stimulus quality and word frequency shown here and in Sheridan and Reingold's (2013) study may hold in the absence of visually salient orthographic cues.

Crucially, the effects of stimulus quality on lexical processing in Experiment 2 showed the same interactive pattern across the three adult age groups. Importantly, these results indicate that while compared to other age groups older adults' reading was more disrupted by reducing text contrast, this was not due to additional difficulties in word recognition. Notably, while Experiment 2 produced interactive effects of contrast and word frequency, additive effects were seen in Experiment 3, suggesting that when the foveal word is presented normally and parafoveal information is presented with contrast reduced, lexical processing is not affected.

Rayner et al.'s (2006) E-Z reader simulations of older adults' reading behaviour (See Chapter 1, Section 1.3.6) included changes to parameter ε, which modulates the effect of visual acuity limitations on the rate of lexical processing. However the present study suggests stimulus quality affects older adults' reading behaviour independently of lexical processing. It therefore could be that other mechanisms also are crucial in accounting for changes in the effects of stimulus quality across the lifespan, such as the duration of the pre-attentive visual processing "V" in E-Z reader (see Figure in Chapter 1, Section 1.3.4). In this stage, low spatial frequency information enables programming of saccades to words and high spatial frequency information enables letter features to be processed. Accordingly, the time required for completion of pre-attentive visual processing may be longer for low compared to high contrast text, and this may especially be the case for older readers (discussed further in Chapter 6, Section 6.2.2). This interaction between stimulus quality and lexical processing also provides important support for the notion of interactive stages of processing. This notion is central to several key models of visual word recognition such as the Interactive Activation model (McClelland & Rumelhart, 1981) and the Dual-route Cascaded model (Coltheart, Rastle, Perry, Langdon, & Zieglar, 2001) (these models are described in Chapter 1, Section 1.4.3). These implications are discussed further in Chapter 6, Section 6.2.3.

3.5 Conclusion

In conclusion, Experiment 2 and 3 provide novel insights into the effects of text contrast on eye movements during reading across the lifespan. Older readers suffer more than young adults from reductions in text contrast. This increased difficulty is experienced both for text presented entirely at low-contrast, and also when parafoveal text is presented at low-contrast. However, while reducing the contrast of all words within a sentence was found to modulate lexical processing, this effect was similar for all age groups. Thus, the additional difficulty incurred by modulation of text contrast primarily affects older adults' visual, rather than lexical, processing of text. Overall the results indicate that poor text contrast may be an important source of reading difficulty for older adults. Moving on, Experiment 4 and Experiment 5 continues the exploration of adult age differences in early word recognition processes by considering letter position coding processes in young and older adults.

Chapter 4:

Effects of adult ageing on letter position coding

Previous research has established that young adult readers encode letter position flexibly during natural reading (White, Johnson, Liversedge, & Rayner, 2008). Given the visual changes that occur with normal ageing it is important to establish whether letter position coding is equivalent across the lifespan. In two experiments, young (aged 18-25) and older (aged 65+) adults' eye movements were recorded as they read sentences with words containing transposed adjacent letters. Transpositions occurred at the beginning (*rpoblem*), internally (*porblem*), or at the end (*problme*) of words. Both age groups achieved normal levels of comprehension for text including words with transposed letters, indicating that both age groups employ flexible letter position coding. In Experiment 4, the transpositions were present throughout reading, in Experiment 5 a gaze-contingent paradigm was employed such that when the eyes moved past a word with transposed letters it was then presented correctly. Generally, the impact of encountering letter transpositions was similar for young and older adults. However, in Experiment 4, older adults experienced a greater increase in rereading times when word beginning letters were transposed. Experiment 5 highlighted that this additional difficulty likely reflects older adults experiencing a "double-whammy" as they are more likely to reencounter transposed letter nonwords during rereading. The implications of the "double-whammy" are an important consideration for future research exploring adult age differences in reading. Overall, while older adults generally process words more slowly, and have generally greater reading difficulty, this does not appear to originate from differences in letter position coding.

4.1 Introduction

Experiments 4 and 5 examine differences in letter position coding processes between young and older adult readers. For young adult readers of European languages such as English, there is now a wealth of evidence demonstrating that letter position coding is flexible rather than fixed (for a review of letter position coding in other languages, see Frost, 2015). A considerable amount of recent research has focused on how letter positions are encoded (e.g. Andrews, 1996; Forster, Davis, Schoknecht, & Carter, 1987; Grainger & Whitney, 2004; Perea & Lupker, 2003ab; Perea & Lupker, 2004; Perea, Rosa & Gomez, 2005; Perea & Fraga, 2006; Rawlinson, 1999; Schoonbaert & Grainger, 2004; for a recent review, see Grainger, Dufau, & Ziegler, 2017) and led to the development of more sophisticated models of word recognition (discussed further in the following sections, e.g. Davis, 1999; Gomez, Ratcliff & Perea, 2008; Grainger & Van Heuven, 2003; Whitney, 2001). Much research has focused on young adults, and some studies have examined the development of letter position encoding during childhood (Grainger, Lété, Bertrand, Dufau, & Ziegler, 2012; Grainger, Bertrand, Lété, Beyersmann, & Ziegler, 2016; Perea & Estevez, 2008; Perea, Jimenez, & Gomez, 2016; see also Paterson, Read, McGowan, & Jordan, 2015). However, studies to date have not examined effects of normal ageing, although changes in visual abilities may have important influences on the processing of letter identities and positions during reading. Therefore, the current study explores letter position coding in young and older adults. The following sections summarise finding to date from the young adult literature on letter position coding, first in studies of isolated word recognition and then in studies of sentence reading, including the importance of letters in different positions and models of letter position coding.

Transposed letter non-words

Letter position coding has been studied experimentally using several paradigms. A common approach involves using pseudowords created by swapping two (usually adjacent) letters within a word (e.g. presenting *judge* in place of *judge*), known as transposed letter (TL) nonwords (see Chapter 1, Section 1.4.2). Single word priming tasks have found that TL nonwords are more effective as a prime in lexical decision tasks than words formed using letter substitutions (Perea, & Lupker, 2003ab; Perea & Lupker, 2004). In addition, TL nonwords produce associative priming (e.g., *jugde* primes COURT; Perea, Palti, & Gómez, 2012) and provide as much facilitative priming as correctly spelled primes in naming tasks (Christianson, Johnson and Rayner, 2005).

Transposed letter non-words in sentence reading

The present study focuses on examining letter position coding during normal sentence reading by examining reading of sentences including words with transposed letters. For young adults reading English, several studies have shown, in line with the notion of flexible letter position coding, readers' comprehension for sentences containing TL nonwords is very good, although transpositions lead to increased reading times (Blythe, Johnson, Liversedge, & Rayner, 2014; Johnson & Eisler, 2012; Rayner, White, Johnson, & Liversedge, 2006; White et al., 2008; see also: Johnson, 2009; Johnson & Dunne, 2012; Velan & Frost, 2007). As transpositions can be read with relative ease, White et al. (2008) concluded that the increase in reading times is primarily due to difficulty with attaining understanding on individual words, rather than a general failure to identify words, supporting the notion of flexible letter position coding. These studies demonstrate that while the specific letters of a word are critical for normal recognition, precise letter position appears to be less crucial. Overall, there is now strong evidence suggesting that TL nonwords enable access to the lexical representation of their base word. However, whether these effects change with age remains to be determined.

Importantly, studies with young adults have shown that not all letters contribute equally to the process of word recognition. Numerous studies reveal a privileged role for the external letters in words (Carr, Lehmkuhle, Kottas, Astor-Stetson, & Arnold, 1976; Forster, 1976; Guérard, Saint-Aubin, Poirier, & Demetriou, 2012; Johnson & Eisler, 2012; Rayner & Kaiser, 1975) and especially the importance of the first letter (Aschenbrenner, Balota, Weigand, Scaltritti, & Besner, 2017). Transposed letter effects in sentence reading (Johnson & Eisler, 2012; Johnson, Perea & Rayner, 2007; Rayner et al., 2006; White et al., 2008) have also shown a clear influence of transpositions at different postions within a word. White et al, (2008) found that young adults experienced the largest changes in their reading behaviour when external changes were made to the word, with transpositions of the beginning letters being most disruptive of all.

It is theoretically important to establish why this differential pattern of importance for letters at different positions occurs (this is discussed further in Chapter 6, Section 6.2.3). One simple explanation as to why external letters may be particularly important is that they are easier to extract as they suffer less lateral interference or crowding effects (e.g., Grainger, Tydgat, & Issele, 2010; Levi, 2008; Pelli, Tillman, Freeman, Su, Berger & Majaj, 2007) from other letters, because they are always preceded by, or followed by, a space. Further, the greater importance of the beginning letter suggests that initial and final letters may contribute to word recognition through different processes. It has been postulated that the importance of initial letters could result from early processes occurring while the word is in the parafovea, as beginning letters have greater parafoveal availability (Briihl & Inhoff, 1995; Rayner, Well, Pollatsek & Bertera, 1982). Whereas, final letters might be more important during later stages of word recognition, such as activating semantic information associated with the word (Perea & Lupker, 2003). However, White et al. (2008) found that the beginning letter retains its privileged role even when parafoveal preview is not available. In line with this, Johnson and Eisler (2012) found that when lateral interference for all letters was equated (by filling spaces with #), the first letter of a word retained its privileged role over interior letters. However, the word final letter no longer played a privileged role when lateral interference was increased. Johnson and Eisler therefore concluded that the importance of the word ending letter arises from low-level visual factors, whereas the word beginning letter has an intrinsic importance in lexical processing (see also, Inhoff, 1990). One suggestion is that the initial letter is especially important for constraining the number of lexical candidates (Broerse & Zwaan, 1966; Clark & O'Regan, 1999; Hand, O'Donnell & Sereno, 2012; Lima & Inhoff, 1985; White et al., 2008). The importance of letters in different positions has also been shown to vary depending on the characteristics of the orthography (Winskel, Ratitamkul, & Perea, in press; for a review of letter position coding in other languages see Frost, 2015).

Crucially, whether letter position coding processes change with age (and in what ways) remains to be established. Many of the visual changes that occur in advanced age may be of relevance to letter position coding (for a discussion of age related visual changes, see Chapter 1, Section 1.2.1). Older adults show reduced sensitivity to fine visual detail (Crassini, Brown & Bowman, 1988; Owlsey, 2011), which may make recognition of individual letters more challenging. This, coupled with older adults' greater sensitivity to the effects of crowding than young adults (Scialfa, Cordazzo, Bubric, & Lyon, 2012), which may result in older adults experiencing "jumbling" of internal letters, may lead to older adults having even greater reliance on external letters than young adults.

Models of letter position coding

The young adult literature has demonstrated the flexibility of letter position coding and also shown that external letters have particular importance for normal, efficient processing. The current study aims to explore whether these patterns also hold for older adults. These findings from the young adult literature have played a vital role in informing models of word recognition, however, as letter position coding in older adults has not been examined, the predictions of word recognition models remain untested for this age group.

In many early models of word recognition (e.g., Dual-Route Cascaded Model, Coltheart, Rastle, Perry, Langdon & Zieglar, 2001; The Interactive-Activation Model, McClelland & Rumelhart, 1981, for a description do these models, see Chapter 1, Section 1.4.3) letter position coding was assumed to be "channel-specific", with letters tagged to their positions early in processing, before letter identity has been encoded. If letter position was fixed in this way, then transposing letters should result in a failure to recognise this word, as it would not activate the associated base word. In addition, according to such models, TL nonwords "*jugde*" are no more similar to the correctly spelled word "*judge*" than the letter substitution nonword "*junpe*", because both of the words share the same number of letters in the correct position. These predictions clearly do not fit with the observed findings (e.g. Perea & Lupker, 2003ab; Perea & Lupker, 2004).

In contrast, some models have been developed with the aim of accounting for letter position coding processes and these models (SERIOL, Whitney, 2001; SOLAR, Davis, 1999, Davis & Bowers, 2006; The Overlap Model, Gomez et al., 2008) view letter position coding as flexible and adopt coding schemes in which "*jugde*" would be processed as more similar to “*judge*” than “*junpe*”, as there is an increase in the number of correct letters (in the case of TL nonwords, all of the correct letters are present), even though they are in the wrong positions. This distinction is particularly important because it is critical to establish the appropriate component mechanism. Models also differ in their predictions about the role of letters in different positions. The SOLAR model (Davis, 1999) relies on spatial coding whereby letter nodes are activated by all constituent letters, with activation reducing as a function of left to right position within a word, therefore, this model would predict that internal letters are more important than word end letters, and so transposing internal letters within a word should be more disruptive than transposing end letters (this does not fit with the observed findings). The SERIOL model (Whitney, 2001) employs continuous open bigram coding which involves encoding of a words constituent letters in terms of all bigrams that can be formed from the word (e.g. dog would be encoded as DO, OG and DG) these bigrams have higher activation if the component letters are close together. The model also specifies that lateral inhibition from adjacent letters can reduce activation. Thus, external letters would have a stronger advantage than internal, and so this model would predict that transpositions of external letters are more disruptive than transpositions of internal letters. To establish a comprehensive account of word recognition, it is vital to explore whether these accounts are accurately reflecting these processes in both young and older readers. For further discussion, see Chapter 6, Section 6.2.3.

4.2 Experiment 4

Despite visual changes such as reduced sensitivity to fine visual detail (Crassini, et al., 1988; Owlsey, 2011), and greater effects of crowding (Scialfa et al., 2012), occurring in older age, previous research has not examined letter position coding processes in older adults. Accordingly, Experiment 4 aimed to: 1) establish whether young and older adults' eye movements differ in response to words with transposed letters, and 2) to examine whether this pattern holds for transpositions in different letter positions. To achieve this, young and older adults read sentences containing words with transposed adjacent letters and answered comprehension questions. In addition to a control condition (no transpositions), three transposition types employed were: beginning TLs (*rpoblem*), internal TLs (*porblem*) and end TLs (*problme*). Participants also completed a nonword circling task. Participants were presented with the same materials that they had read during the experiment, and they were asked to circle any words that they did not understand. Performance in this task, and measures of accuracy in response to comprehension questions during the main experiment, tested whether older readers are able to comprehend TL nonwords. That is, these measures help reveal whether older adults are able to employ flexible letter position coding.

It could be that despite visual declines (e.g. Crassini et al., 1988) older adults process letter position in the same way as young adults. Alternatively, their processing may differ in one of three ways: 1) Older adults may be more flexible (less precise) in their processing and therefore less affected by letter transpositions. 2) Older adults may be more dependent on fixed letter position coding, and so have difficulty reading words with transposed letters (both in the eye movement task and the nonword circling task) or, what is considered the most likely scenario (considering the visual issues older adults experience) 3) they may display flexible letter position coding but with differences in the degree of importance for letters in different positions. Specifically, older adults may experience greater disruption than young adults when external letters within a word are transposed, but less disruption (or even no disruption) when internal letters are transposed, due to the greater visual crowding incurred for internal letters (see Chapter 1, Section 1.2.1).

4.2.1 Method

Participants. Sixteen young adults (*M*= 19.6, range= 18-25 years, 10 female) and sixteen older adults (*M*= 68.6, range= 65-74 years, 9 female) were recruited from the University of Leicester and the surrounding community. Criteria for participation were the same as for previous experiments. The older adults had a lower acuity and lower contrast sensitivity than the young adults ($p<.05$). The two age groups did not differ on years of education and all reported spending several hours reading each week (all *p*s >.05). These participant characteristics are summarised in Table 4.1.

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/17	20/16-20/22	20/27	20/19-20/36
Low contrast near acuity	20/30	20/20-20/38	20/42	20/22-20/53
High contrast distance acuity	20/19	20/14-20/25	20/26	20/18-20/35
Low contrast distance acuity	20/28	20/22-20/35	20/40	20/25-20/53
Screen distance acuity	20/19	20/13-20/30	20/28	20/20-20/35
Contrast-sensitivity	1.97	1.95-2.05	1.88	1.80-1.95
Years of education	15.8	13-18	16.0	10-20
Hours spent reading/week	12.5	6-23	13.2	2-35

Table 4.1. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 4. Appropriate correction was applied to calculate acuity at the distances used.

Materials & Design. 80 sentences (adapted from White et al., 2008) were presented in 4 conditions, forming a 2 (age: young, or older) x 4 (text type: no transposition (normal), word-beginning, internal, word-end) mixed design (examples of each condition shown in Figure 4.1). Half of the sentences in the internal transposition condition contained transpositions near the word beginning (*porblem*) and half contained transpositions located near the word endings (*probelm*) (based on the internal letter transpositions employed by White et al., 2008). Sentences varied in length from 7-15 words (*M*= 10.7). Transpositions were applied to all words containing five or more letters. Each sentence contained at least three words with a transposition with eleven stimuli being adjusted to meet this criterion (adjusted stimuli can be found in Appendix

D). Transpositions always involved adjacent letters. None of the transpositions resulted in the production of a real word, none retained the original spelling of the word and none were proper nouns. The items were counterbalanced so that participants saw an equal number of sentences from each condition. A comprehension question followed 40% of the sentences.

Following the eye tracking session, participants completed a nonword circling task. Participants were asked to circle any words that they did not understand. The stimuli included the sentences that the participants had been presented with in the main experiment, with ten additional items that included random letter string nonwords (e.g. *eoynam*). These items ensured that the task was being carried out properly, as a failure to circle these words as not understood would indicate that the task was not being performed correctly.

Control:

`The teacher gave the difficult anagram as the final question.`

Beginning TLs:

`The etacher gave the idfficult naagram as the ifnal uqestion.`

Internal TLs:

`The teacehr gave the difficlut anagarm as the fianl questoin.`

End TLs:

`The teachre gave the difficutl anagrma as the finla question.`

Figure 4.1. Experiment 4. An example sentence in each condition.

Apparatus. The apparatus was identical to that used in Experiments 1, 2 and 3.

Procedure. Before commencing the eye tracking session, participants received instructions stating: “Some of the letters in some of the words may be mixed up. However, you will probably be able to guess what most of these words mean. Therefore please concentrate on understanding the sentences to the best of your ability.” The rest of the eye tracking procedure was the same as in previous experiments. At the end of the session participants completed the nonword circling task, they were instructed to circle any words that they did not understand.

Analyses. Following standard procedures, fixations shorter than 80ms or longer than 1,200ms were discarded. This accounted for 1.7% of fixations. The data were analysed using linear mixed effects models (LMEM; Baayen, Davidson, & Bates, 2008) conducted using R (R Core Team, 2015) and the lme4 package (Bates, Maechler & Bolker, 2011). First, Type II model comparisons were used to determine main effects of condition using the ANOVA function of the car package (Fox, Friendly, & Weisberg, 2013). Following this, analyses were conducted using the normal condition as a baseline, with each transposition condition compared against this. These contrasts were coded using an inverse contrast matrix (such that for each contrast the TL condition was coded as -.5 and the normal condition was coded as .5). In addition, the contrasts for age were defined using sliding contrasts in the MASS package (Venables & Ripley, 2002). Both age-group (young, older) and text type (normal vs. beginning TLs; normal vs. internal TLs; normal vs. end TLs) were included as fixed effects in the LMEMs. To examine significant interactions between age and text type, follow up contrasts were conducted comparing the normal condition and the relevant transposition condition separately for each age group. Based on the findings of White et al, (2008) it was anticipated that word-beginning transpositions would be the most disruptive to reading, it was also anticipated that end transpositions would be more disruptive than internal transpositions. To examine this, sliding contrasts were defined comparing the word-end to the word-beginning condition, and the internal condition to the word-end condition. Again, sliding contrasts were also used to define age group and this produced 2 x 2 comparisons of age group and transposition condition. Following current practice, a maximal random effects structure was used (following Barr, Levy, Scheepers & Tily, 2013)[8]. Participants and stimuli were specified as crossed-random effects, age-group and text type were specified as fixed factors. For all analyses, *t* values >1.96 were considered significant.

Several sentence-level measures are presented: sentence reading time, average fixation duration, number of fixations, number of regressive saccades and number of first-pass skips. First-pass reading times and rereading times are also reported.

[8] All maximal models converged. Analyses for continuous variables were undertaken on both the raw data and log-transformed data, although only the analyses for the raw data are reported. Unless stated otherwise, significance patterns were the same for both sets of data. For measures including zero values, a small amount (less than one) was added to each zero to allow log-transformation of these data.

Definitions for all of these measures can be found in Chapter 1, Section 1.3.4. All analyses include all words within a sentence[9].

4.2.2 Results

Comprehension & nonword circling task. The comprehension questions (following 40% of sentences) were answered with a high degree of accuracy, with all participants achieving at least 85% (*M*= 93%), of questions answered correctly. *t*-tests on the comprehension scores showed that these did not differ by age or by text type (all *p*s> .300). For the nonword circling task both the young and older adults successfully circled a large majority of the random letter string non-words (e.g. *eoynam*), indicating that participants were completing the task appropriately (young adults; *M*= 9.0/10, range= 8-10, older adults; *M*=9.2/10, range 8-10). Most participants circled no TL nonwords at all (24/32 participants) and no individual participant circled more than two TL nonwords in total. The number of TL nonwords that could not be understood did not differ by age-group or by transposition condition (*p*s> .300). Together the sentence comprehension and nonword circling results indicate that comprehension of TL nonwords was very high for both young and older adults. These measures indicate that during the eye movement experiment the TL nonwords were likely understood by both groups.

Eye movement measures. Means and standard errors are presented in Table 4.2. Effects of age are first examined only for the normal (no transposition) text condition. Older adults produced longer reading times (β= 737.70, *SE*= 240.80, *t*= 3.06), made more fixations (β= 2.32, *SE*= 0.86, *t*= 2.71), more regressive saccades (β= 1.84, *SE*= 0.41, *t*= 4.51), spent more time rereading (β= 615.19, *SE*= 144.44, *t*= 4.26) and skipped more words on first-pass than young adults (although this did not quite reach significance, β= 0.54, *SE*= 0.29, *t*= 1.94). Young and older adults produced similar average fixations durations (β= 0.05, *SE*= 6.99, *t*= 0.01) and first-pass reading times (β= 99.78, *SE*= 130.48, *t*= 0.77). These results demonstrate a decline in reading efficiency in older age in line with previous research (e.g. Rayner, Reichle et al., 2006).

[9] Additional analyses were undertaken taking into account only a critical word (this word was always at least 5 letters long, and so always contained transposition) and all words containing a transposition. In both cases the pattern of results was consistent with the sentence-level analyses.

There were significant effects of age for four of the measures, in line with results for the normal text condition, older adults produced longer sentence reading times, made more fixations, more regressive saccades and had longer rereading times compared to young adults. Further, reading sentences containing TL nonwords slowed reading. There were significant main effects of text-type for all measures (sentence reading time F= 34.18, fixation duration F= 18.60, number of fixations F= 26.20, number of regressions F= 11.49, first-pass reading time F= 29.71, rereading time F= 13.05, number of first-pass skips F= 13.00, in all cases p<.001)

Transpositions at beginning, internal and end positions all produced longer sentence reading times, fixation durations, more fixations, fewer first-pass skips, longer first-pass reading times and longer rereading times than in the normal text condition. There were also more regressive saccades in the beginning TL and end TL conditions compared to the normal condition (see Figures below). The results of the LMEM analyses for effects of age-group (young vs. older) and text type (normal vs. beginning TLs; normal vs. internal TLs; normal vs. end TLs are summarised in Table 4.3. Figures 4.2-4.4. display graphs for key measures.

There were no interactions between age and text type for measures sensitive to only first-pass reading behaviour (first-pass reading time and the number of first-pass skips), nor for average fixation duration or the number of regressive saccades. There were, however, interactions between age and text type for sentence reading time and rereading time, but only for the contrast of the normal vs. beginning TL conditions. (A similar pattern was shown for the number of fixations, but this did not reach significance in the analysis of log-transformed data.) Beginning TLs resulted in greater disruption for older, compared to young, adults during rereading (this can be seen in Figure 4.4).

To examine the influence of transpositions at different positions within a word, sliding contrasts were used to produce comparisons of the beginning vs. end TL conditions and the end vs. internal TL conditions (based on previous findings: White et al., 2008; Johnson & Eisler, 2012). LMEM statistics for these analyses are summarised in Table 4.4. These contrasts revealed that greater disruption occurred in the beginning compared to the end transposition condition for all measures except number of first-pass skips. End TLs produced greater disruption than internal TLs for all measures except fixation durations, which were similar across the two conditions. This pattern of results is in line with previous research (e.g. Guérard et al., 2012; Johnson & Eisler, 2012; White et al., 2008), and demonstrates the importance of external letters, and beginning letters in particular, for word recognition. There were no interactions between age-group and transposition type for the contrast of end vs. internal TLs or beginning vs. end TLs (although this interaction approached significance in rereading times).

	Normal	Beginning TLs	Internal TLs	End TLs
Sentence reading time (ms)				
Young	2454 (173)	3291 (252)	2646 (191)	3040 (255)
Older	3152 (245)	4516 (357)	3583 (271)	4055 (361)
Fixation duration (ms)				
Young	243 (5)	259 (6)	250 (5)	252 (5)
Older	243 (7)	262 (8)	250 (7)	253 (7)
Number of fixations				
Young	10.1 (0.6)	12.3 (0.7)	10.4 (0.6)	12.0 (0.9)
Older	12.2 (0.8)	16.1 (1.1)	13.5 (0.9)	14.9 (1.2)
Number of regressive saccades				
Young	1.8 (0.3)	2.6 (0.4)	1.9 (0.3)	2.1 (0.3)
Older	3.6 (0.4)	5.1 (0.6)	3.9 (0.4)	4.4 (0.4)
First-pass reading time				
Young	1965 (129)	2374 (161)	2079 (155)	2273 (163)
Older	1856 (134)	2682 (183)	1890 (151)	1964 (160)
Number of first-pass skips				
Young	3.6 (0.2)	3.2 (0.2)	3.6 (0.2)	3.3 (0.1)
Older	4.1 (0.3)	3.8 (0.2)	3.8 (0.3)	3.7 (0.3)
Rereading time				
Young	436 (138)	786 (197)	513 (128)	653 (163)
Older	1034 (203)	1794 (340)	1234 (252)	1413 (293)

Table 4.2. Experiment 4. Means (and standard errors) for young and older adults in each condition.

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time (ms)	Number of first-pass skips	Rereading time (ms)
Intercept	***β***	3346.73	251.54	12.69	3.16	2143.08	3.70	983.79
	SE	148.47	3.69	0.51	0.26	80.55	0.19	94.81
	t	22.54*	68.28*	24.65*	12.11*	26.61*	18.97*	10.38*
Age								
Young vs. Older	***β***	964.90	0.76	2.94	3.41	64.21	0.40	771.05
	SE	287.92	7.20	1.00	0.47	158.20	0.32	183.27
	t	3.35*	0.11	2.94*	4.21*	0.41	1.44	4.21*
Text Type								
Normal vs. word-beginning	***β***	1112.81	17.63	3.09	1.10	417.63	0.34	563.26
	SE	102.62	2.33	0.30	0.18	47.72	0.07	83.04
	t	10.84*	7.56*	10.16*	5.95*	8.75*	4.80*	6.78*
Normal vs. Internal	***β***	316.21	6.83	0.82	0.12	154.16	0.13	137.42
	SE	57.53	2.23	0.18	0.11	29.51	0.06	57.83
	t	5.50*	3.06*	4.59*	1.13	5.22*	2.16*	2.38*
Normal vs. word-end	***β***	744.40	9.22	2.33	0.50	353.52	0.34	299.14
	SE	97.31	1.94	0.30	0.13	36.68	0.06	87.67
	t	7.65*	4.75*	7.81*	3.70*	9.64*	5.98*	3.41*
Age x Text Type								
Age x Normal vs. word-beginning	***β***	504.26	2.54	1.60	0.45	3.89	0.12	398.86
	SE	172.93	4.53	0.52	0.33	92.88	0.12	147.44
	t	2.92*	0.56	3.09*	1.39	0.04	0.97	2.71*
Age x Normal vs. Internal	***β***	236.75	1.47	0.96	0.03	90.91	0.12	116.46
	SE	110.67	4.39	0.35	0.22	54.54	0.13	109.47
	t	1.48	0.34	1.76	0.13	1.66	1.40	1.06
Age x Normal vs. word-end	***β***	305.89	1.43	0.91	0.26	81.36	0.05	163.18
	SE	183.04	3.75	0.55	0.26	70.97	0.11	170.35
	t	1.67	0.38	1.66	1.01	1.14	0.45	0.96

Table 4.3. Experiment 4. LMEM statistics with normal condition as baseline. Significant effects are indicated by an asterisk (*).

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time (ms)	Number of first-pass skips	Rereading time (ms)
Intercept	***β***	3346.73	251.54	12.69	3.16	2143.08	3.70	983.79
	SE	148.47	3.69	0.51	0.26	80.55	0.19	94.81
	t	22.54*	68.28*	24.65*	12.11*	26.61*	18.97*	10.38*
Age								
Young vs. Older	***β***	964.90	0.76	2.94	3.41	64.21	0.40	771.05
	SE	287.92	7.20	1.00	0.47	158.20	0.32	183.27
	t	3.35*	0.11	2.94*	4.21*	0.41	1.44	4.21*
Text Type								
Internal vs. Word-end	***β***	403.88	1.67	1.40	0.37	205.88	0.21	135.50
	SE	81.47	2.01	0.27	0.13	33.33	0.06	67.25
	t	4.96*	0.83	5.28*	2.97*	6.18*	3.40*	2.80*
Word-end vs. Word-beginning	***β***	391.47	8.71	0.94	0.60	58.55	0.01	277.53
	SE	84.62	1.76	0.29	0.14	32.75	0.06	77.48
	t	4.63*	4.95*	3.23*	4.22*	1.97*	0.07	3.58*
Age x Text Type								
Age x Internal vs. Word-end	***β***	41.96	2.82	0.14	0.23	40.75	0.12	19.50
	SE	154.86	3.54	0.50	0.24	63.02	0.12	125.55
	t	0.27	0.80	0.28	0.97	0.65	1.02	0.16
Age x Word-end vs. Word-beginning	***β***	168.72	0.49	0.51	0.20	56.69	0.17	244.57
	SE	148.13	3.52	0.50	0.26	58.63	0.11	135.31
	t	1.14	0.14	1.01	0.76	0.97	1.55	1.81

Table 4.4. Experiment 4. LMEM statistics for sliding contrasts. An asterisk (*) represents significant effects.

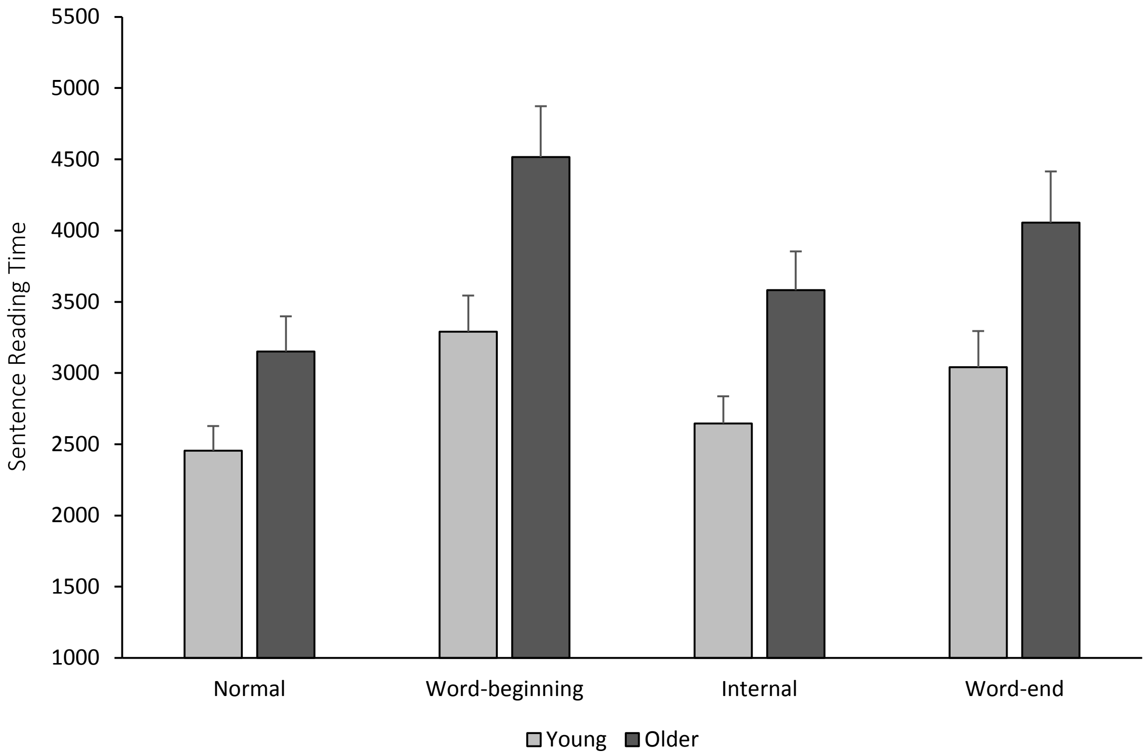

Figure 4.2. Experiment 4. Mean sentence reading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

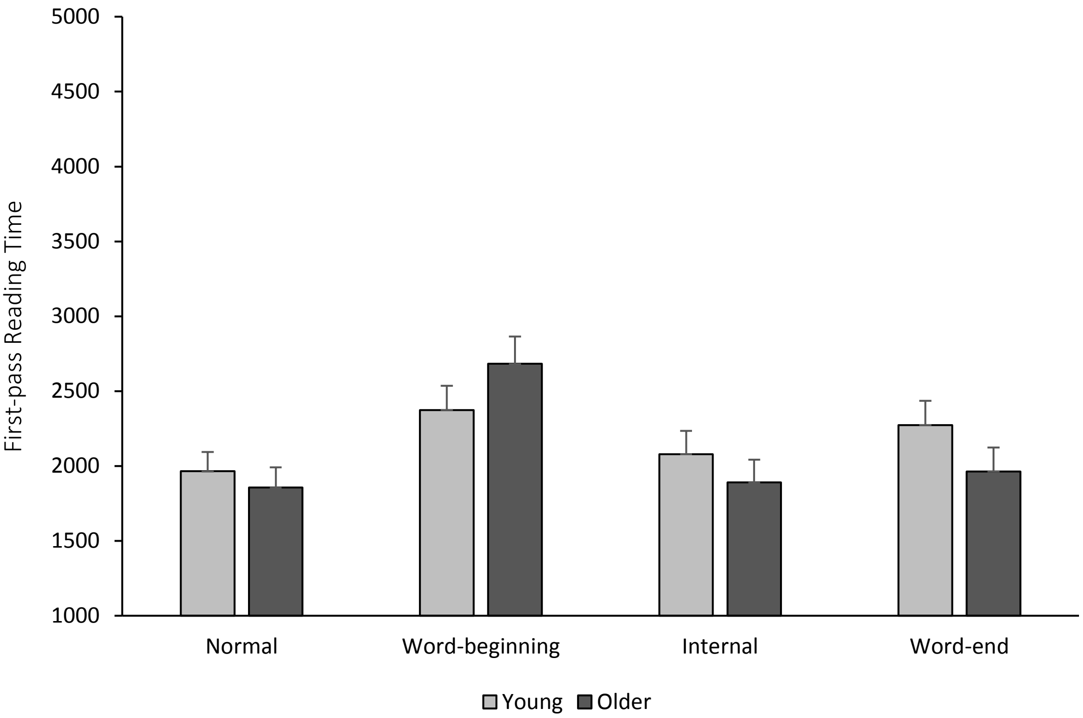

Figure 4.3. Experiment 4. Mean first-pass reading time for each age-group in each condition. Error bars correspond to one standard error.

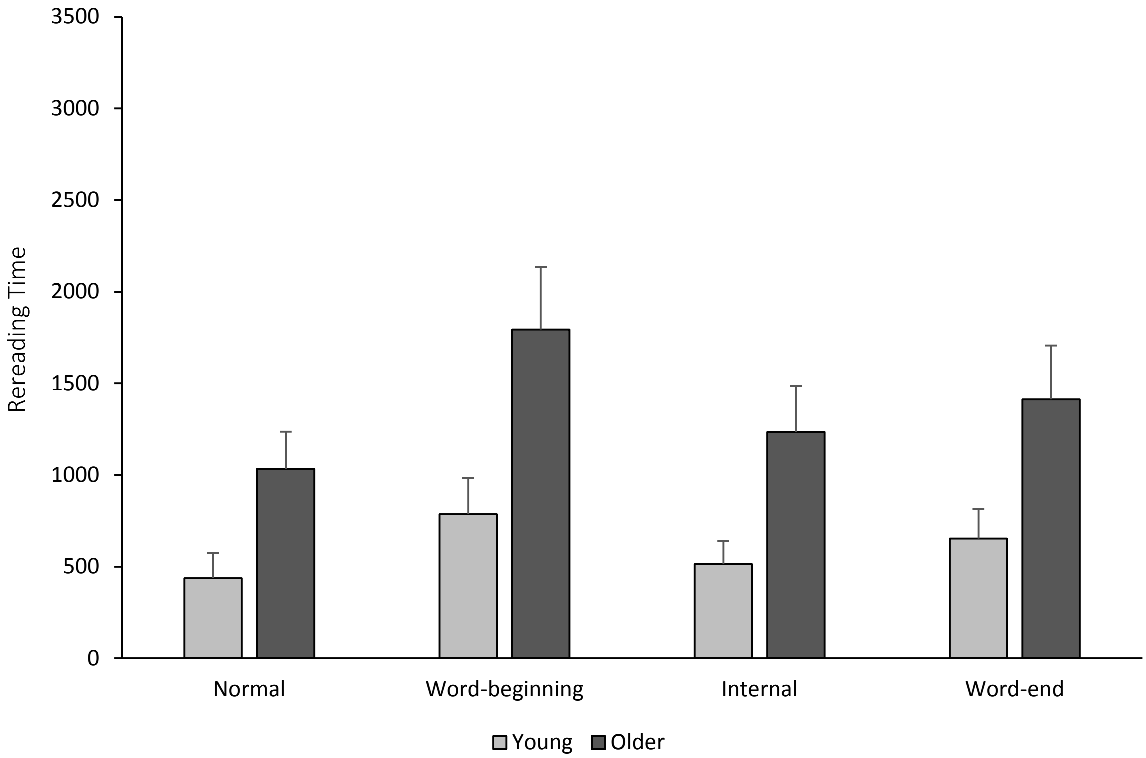

Figure 4.4. Experiment 4. Mean rereading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

4.2.3 Discussion

Despite displaying generally greater reading difficulty than the young adults as indicated by longer reading times (e.g. Rayner, Reichle et al., 2006, see also Appendix A for a comparison with other experiments in this thesis), older adults were able to successfully read and comprehend words including transpositions of beginning, internal and end letters (as demonstrated by performance in the nonword circling task and high levels of accuracy for the comprehension questions). The results of Experiment 4 therefore provide important evidence for the use of flexible letter position coding by both young and older adults.

Importantly, in line with previous findings for young adults (Blythe et al., 2014; Johnson & Eisler, 2012; White et al., 2008), the eye movement measures show that both age groups were sensitive to transpositions in all positions within a word. This indicates that despite changes occurring to visual abilities in advanced age (see Chapter 1, Section 1.2.1), such as increased sensitivity to visual crowding (Scialfa et al., 2012) and decreased sensitivity to fine visual detail (Crassini, et al. 1988; Owlsey, 2011), the position of internal letters within words remains important for word recognition for both young and older readers.

Further, these results provide support for the notion that external letters are particularly crucial for word identification, with the beginning letter being the most important of all (this is discussed further in Section 4.4 and Chapter 6, Section 6.2.3) Guérard et al., 2012; Johnson & Eisler, 2012; Rayner, White et al., 2006; White et al. 2008). Interestingly, reading difficulty incurred by the beginning TLs was especially pronounced for the older readers, specifically for measures sensitive to rereading. These results might be interpreted as differences in letter position coding between young and older adults limited to the later stages of word recognition. However, as differences between young and older readers were only found for later measures, and not for early word processing measures (when letter position coding is taking place), this raises the question of whether these differences indeed represent processing differences in letter position coding between young and older adults. However, note that older adults made more regressive saccades and spent more time rereading than young adults in the normal reading condition, in line with the typical characterisation of older adults' eye movement behaviour (Rayner, Reichle et al., 2006, for a comparison to the other experiments in this thesis, see Appendix A). One possibility is that as a consequence of older adults' more extensive rereading, there is a greater likelihood of words being revisited, including the more difficult to process TL nonwords. Consequently, rereading times associated with TL nonwords may be inflated for older adults, not because of differences in letter position coding, but perhaps simply due to a greater likelihood of TL nonwords being read multiple times. In addition, the increase in rereading time was not accompanied by an increase in the number of regressive saccades occurring, as although a main effect of age was found, no interactions were observed, rather, a greater time is spent rereading when a regression does occur. Therefore, it could be that older adults are experiencing a "double-whammy" due to processing difficulty triggered by both first-pass and rereading of words with transposed letters. This possibility is explored in Experiment 5.

4.3 Experiment 5

To examine the nature of the increased rereading observed in Experiment 4, Experiment 5 employed a gaze-contingent paradigm such that when the eyes moved past each TL nonword these words were then presented correctly (e.g. *probelm* changed to *problem*), unlike Experiment 4 where the transpositions were present throughout the reading process. If the larger effects of beginning transpositions for older adults shown in Experiment 4 is likely a result of a greater likelihood of repeated processing of the words during rereading (a “double-whammy” effect) then the gaze-contingent manipulation in Experiment 5 should eliminate the interaction. Experiment 5 therefore provides a further test of whether letter position coding is similar for young and older adults. If the effects of age and transposition type are additive in Experiment 5 then this will be consistent with the suggestion that letter position coding processes are not modulated by adult age.

4.3.1 Method

Participants. Sixteen young adults (*M*= 19.4 years, range= 18-24, 10 female) and 16 older adults (*M*= 69 years, range= 65-77, 10 female) were recruited from the University of Leicester and the surrounding community. None took part in Experiment 4. Criteria for participating were the same as in Experiment 4 and participants’ visual abilities were assessed using the same tests. Older adults had poorer visual acuity and contrast sensitivity (*p*s< .05). Participants were well matched on years of education and all reported reading for several hours each week (*p*s> .05). In addition to the data reported, two older adults were excluded due to poor vision and/or tracking difficulties. These participant characteristics are summarised in Table 4.5.

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/18	20/14/20/24	20/28	20/19-20/35
Low contrast near acuity	20/32	20/20-20/40	20/44	20/24-20/50
High contrast distance acuity	20/18	20/14-20/25	20/27	20/20-20/34
Low contrast distance acuity	20/30	20/22-20/35	20/42	20/26-20/50
Screen distance acuity	20/18	20/14/20/28	20/27	20/19-20/34
Contrast-sensitivity	1.96	1.93-2.05	1.88	1.80-1.95
Years of education	15	13-17	14.9	11-22
Hours spent reading/week	10.8	4-25	12.2	5-35

Table 4.5. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 5. Appropriate correction was applied to calculate acuity at the distances used.

Materials and design. The same materials as in Experiment 4 were used. Experiment 5 employed a variation of the gaze-contingent boundary change paradigm (McConkie & Rayner, 1975). Once a reader made a progressive eye movement beyond a TL nonword this was replaced with the correctly spelled word (Figure 4.2). That is, once the eyes moved past a TL nonword, the leftward parafoveal postview of the word was always spelled correctly, and the word continued to be correctly spelled for the remainder of the trial, including during any subsequent rereading.

```
                                    *
The teacher gave the difficult naagram as the ifnal uqestion.

                                            *
The teacher gave the difficult anagram as the ifnal uqestion.

                                    *
The teacher gave the difficult anagram as the ifnal uqestion.
```

Figure 4.5. Experiment 5. A demonstration of the gaze-contingent manipulation in the beginning transposition condition (this manipulation was employed for all TL conditions). An asterisk (*) represents the point of fixation.

Apparatus. The apparatus used were the same as in Experiment 4.

Procedure & Analyses. The general procedure and analyses were the same as for the eye tracking component of Experiment 4. As in Experiment 4, fixations shorter than 80ms or longer than 1,200ms were discarded. This accounted for 1.6% of fixations.

4.3.2 Results

Comprehension. Comprehension accuracy was high, with all participants achieving at least 85% (M= 95%). t-tests revealed that comprehension did not differ by age or by text type (all ps> .300). This further indicates that both young and older adults are able to successfully read and comprehend sentences including words with transposed adjacent letters.

Eye movement results. Means and standard errors are presented in Table 4.6. Effects of age are first examined using LMEM analyses only for the normal text condition. Older adults produced longer reading times and skipped more words on first-pass than young adults (t >1.96). There were further numerical trends which did not reach significance for number of regressive saccades and rereading time. These results demonstrate standard effects of older age in reading and suggest a decline in reading efficiency in older age in line with previous research (e.g. Rayner, Reichle et al., 2006, for a comparison to the other studies in this thesis, see Appendix A).

There were significant main effects of text-type for all measures (sentence reading time F= 38.27, fixation duration F= 36.06, number of fixations F= 33.67, number of regressions F= 10.43, first-pass reading time F= 55.62, rereading time F= 6.52, number of first-pass skips F= 5.13, in all cases p<.01). The results of the LMEM for effects of age group (young vs. older) and text type (normal vs. beginning TLs; normal vs. internal TLs; normal vs. end TLs) summarised in Table 4.7. In line with the normal text condition older readers had significantly longer sentence reading times and made significantly more regressive saccades than younger readers. Reading TL nonwords produced longer reading times than normal, and this was the case for transpositions in every position, in line with Experiment 4. All transposition types produced longer sentence reading times, fixation durations, more fixations, more regressive saccades, longer first-pass reading times and longer rereading times than the normal text condition. The number of first-pass skips did not differ from normal in the internal transposition condition. Crucially, unlike in Experiment 4, there were no interactions between age-group and any of the effects of text type.

As in Experiment 4, to examine the influence of transpositions at different positions within a word, additional models were conducted with sliding contrasts that compared the beginning vs. end TL conditions, and the end vs. internal TL conditions. LMEM statistics associated with these contrasts are shown in Table 4.8. These contrasts revealed that greater disruption occurred in the beginning TL condition compared to the end condition for all measures except number of first-pass skips (although this difference did approach significance). A similar pattern was found in comparisons of the internal and the end TL conditions, with end TLs resulting in greater disruption than internal TLs for most measures with the exception of number of regressive saccades and time spent rereading the sentence. Importantly, this pattern of effects was similar for both young and older adults and there were no interactions with age. The results therefore demonstrate the importance of external letters and the particular importance of the beginning letter in word recognition for both young and older adults.

In addition to the LMEM analyses, Bayes factors were calculated to assess the strength of evidence for the null interactions in Experiment 5. These were computed using the BayesFactor package (Morey & Rouder, 2015) in R (R Core Team, 2015), with the scaling factor for g-priors set to 0.5 and using 100,000 Monte Carlo iterations. Participants and items were specified as random effects. Following Vandekerckhove, Matzke, and Wagenmakers (2014; adapted from Jeffreys, 1961), BFs > 3 were taken to provide weak to moderate support for a model and BFs > 10 to provide strong support, while BFs < 1 were taken to provide evidence against a model and in favour of the alternative (or null) model. For each measure, the null model was determined by the LMEM analyses e.g. where there were both main effects of age group and main effects of condition, a model containing these effects was taken as the null model. Bayes factors were calculated separately for each LMEM contrast. In all cases, support was found for a null model over a model containing an interaction between age group and text type (all BFs < 0.4). Thus, the interactions in Experiment 4 were eliminated in Experiment 5, young and older adults responded similarly to reading words with transposed letters for all of the measures.

	Normal	Beginning TLs	Internal TLs	End TLs
Sentence reading time (ms)				
Young	2545 (265)	3439 (337)	2885 (285)	3078 (293)
Older	2762 (248)	3599 (355)	3175 (219)	3288 (258)
Fixation duration (ms)				
Young	223 (9)	245 (10)	232 (9)	234 (9)
Older	229 (7)	249 (7)	238 (6)	241 (6)
Number of fixations				
Young	10.0 (0.8)	12.3 (0.9)	10.8 (0.8)	11.5 (0.8)
Older	10.4 (0.8)	12.6 (1.0)	11.6 (0.7)	11.9 (0.9)
Number of regressive saccades				
Young	2.4 (0.4)	3.1 (0.4)	2.6 (0.3)	2.7 (0.4)
Older	2.8 (0.4)	3.4 (0.4)	3.1 (0.3)	3.0 (0.4)
First-pass reading time				
Young	1968 (164)	2403 (181)	2159 (168)	2273 (182)
Older	1933 (96)	2409 (140)	2190 (106)	2263 (113)
Number of first-pass skips				
Young	4.4 (0.2)	4.4 (0.2)	4.4 (0.2)	4.2 (0.2)
Older	4.9 (0.2)	4.7 (0.2)	4.7 (0.2)	4.5 (0.2)
Rereading time				
Young	723 (151)	1059 (151)	892 (134)	884 (120)
Older	793 (129)	1131 (210)	923 (129)	901 (138)

Table 4.6. Experiment 5. Means (and standard errors) for young and older adults in each condition.

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time	Number of first-pass skips	Rereading time
Intercept	***β***	3120.31	236.28	11.46	2.74	2200.63	4.54	798.78
	SE	201.84	5.82	0.61	0.24	104.86	0.18	93.20
	t	15.46*	40.59*	18.92*	11.61*	20.99*	25.55*	8.57*
Age								
Young vs. Older	***β***	226.07	5.95	0.52	0.60	1.60	0.31	67.70
	SE	395.37	11.55	1.18	0.46	204.91	0.29	183.20
	t	1.96*	0.52	1.63	2.31*	0.08	1.47	1.59
Text Type								
Normal vs. Word-beginning	***β***	907.67	20.70	2.30	0.72	474.75	0.15	361.52
	SE	90.00	1.95	0.24	0.12	35.98	0.06	79.22
	t	10.09*	10.64*	9.62*	5.78*	13.20*	2.47*	4.56*
Normal vs. Internal	***β***	360.22	8.93	0.97	0.24	225.26	0.08	191.79
	SE	62.78	1.84	0.21	0.12	28.69	0.05	97.87
	t	5.74*	4.86*	4.71*	2.03*	7.85*	1.51	1.96*
Normal vs. Word- End	***β***	506.90	11.74	1.39	0.22	321.45	0.26	179.59
	SE	57.82	2.11	0.18	0.10	35.17	0.06	66.84
	t	8.77*	5.58*	7.51*	2.09*	9.14*	4.12*	2.69*
Age x Text Type								
Age x Normal vs. Word-beginning	***β***	140.53	0.77	0.41	0.38	54.44	0.15	72.74
	SE	160.60	3.37	0.47	0.22	67.04	0.12	154.33
	t	0.88	0.23	0.88	1.30	0.81	1.27	0.47
Age x Normal vs. Internal	***β***	191.27	1.77	0.63	0.39	75.49	0.12	60.56
	SE	125.33	3.35	0.40	0.23	56.06	0.10	188.76
	t	1.33	0.53	1.38	1.39	1.33	1.21	0.32
Age x Normal vs. Word-End	***β***	63.95	2.15	0.06	0.17	17.37	0.19	46.55
	SE	111.89	4.11	0.37	0.20	66.55	0.12	131.47
	t	0.57	0.52	0.17	0.86	0.26	1.55	0.35

Table 4.7. Experiment 5. LMEM statistics for analyses with normal condition as baseline. Significant effects are indicated by an asterisk (*).

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time (ms)	Number of first-pass skips	Rereading time (ms)
Intercept	***β***	3120.31	236.28	11.46	4.54	2200.63	2.74	798.78
	SE	201.84	5.82	0.61	0.18	104.86	0.24	93.20
	t	15.46*	40.59*	18.92*	25.55*	20.99*	11.61*	8.57*
Age								
Young vs. Older	***β***	226.07	5.95	0.52	0.31	1.60	0.60	67.70
	SE	395.37	11.55	1.18	0.29	204.91	0.46	183.20
	t	1.96*	0.52	1.63	1.87	0.08	2.31*	1.99*
Text Type								
Internal vs. Word-end	***β***	150.03	2.86	0.42	0.18	96.64	0.01	11.93
	SE	62,25	1.61	0.19	0.06	26.45	0.11	82.71
	t	2.41*	1.98*	2.25*	3.23*	3.65*	0.21	0.14
Word-end vs. Word-beginning	***β***	400.69	8.95	0.92	0.11	153.30	0.50	181.93
	SE	73.73	2.04	0.22	0.06	32.11	0.13	73.36
	t	5.43*	4.38*	4.15*	1.86	4.77*	3.88*	2.48*
Age x Text Type								
Age x Internal vs. Word-end	***β***	107.89	0.87	0.54	0.02	51.85	0.22	97.85
	SE	122.28	3.23	0.38	0.11	52.35	0.21	159.15
	t	0.88	0.27	1.45	0.21	0.99	1.04	0.62
Age x word-end vs. Word-beginning	***β***	76.59	1.38	0.35	0.04	37.08	0.21	119.30
	SE	136.88	3.86	0.42	0.11	51.89	0.22	139.14
	t	0.56	0.36	0.83	0.38	0.72	0.94	0.86

Table 4.8. Experiment 5. LMEM statistics for sliding contrasts. Significant effects are indicated by an asterisk (*).

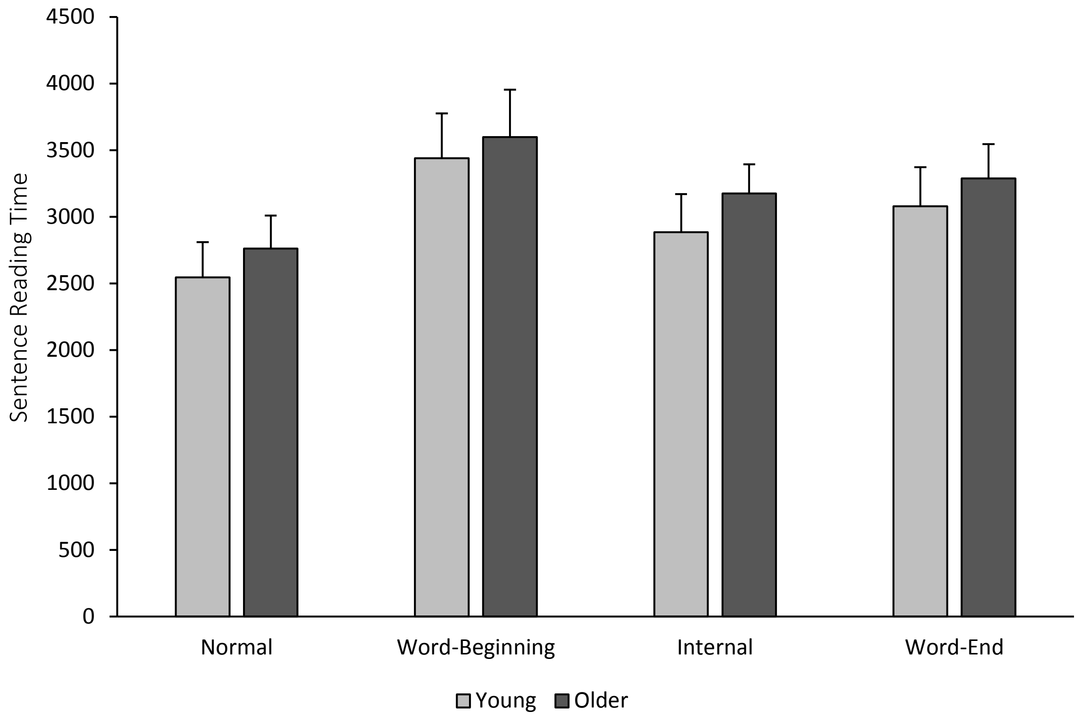

Figure 4.6. Experiment 5. Mean sentence reading time for each age-group in each condition. Error bars correspond to one standard error.

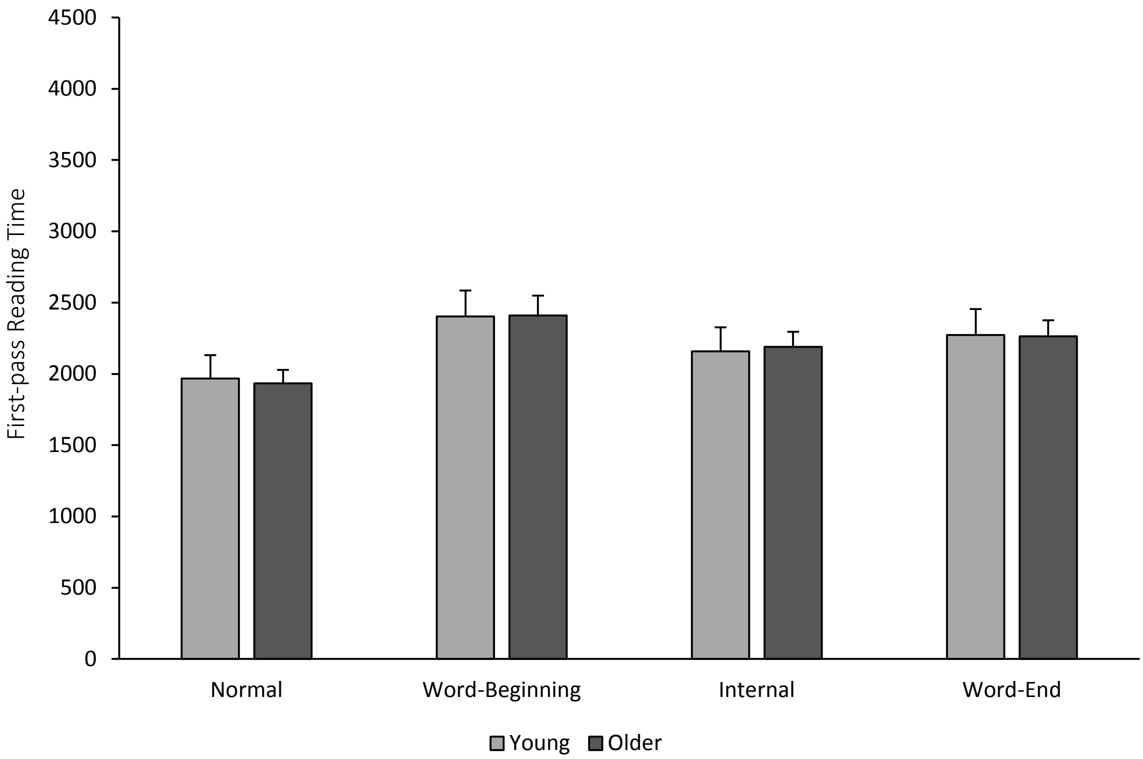

Figure 4.7. Experiment 5. Mean first-pass reading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

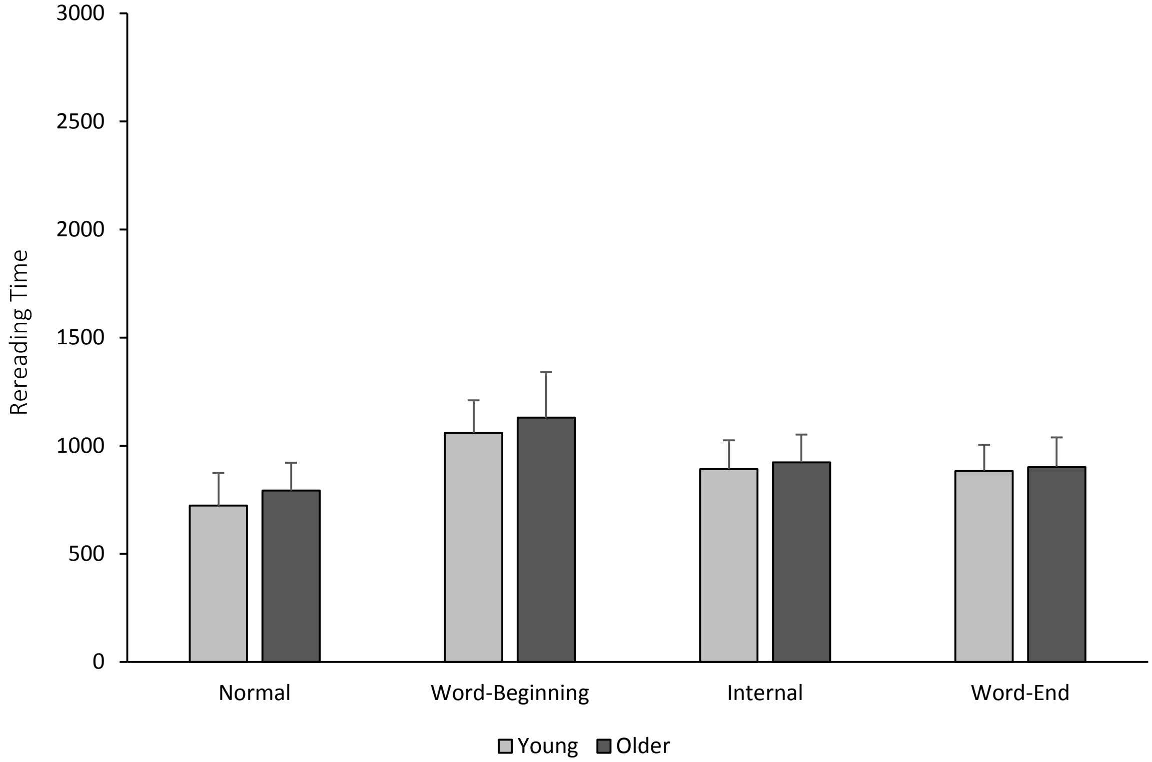

Figure 4.8. Experiment 5. Mean rereading time (ms) for each age-group in each condition. Error bars correspond to one standard error.

4.3.3 Discussion

In Experiment 5 older adults displayed standard adult age differences when reading normally presented text, displaying longer reading times and more regressive saccades in line with both previous research (e.g. Rayner, Reichle et al., 2006) and with the results of Experiment 4 (for a comparison with the other experiments in this thesis, see Appendix A). Both age-groups were sensitive to transpositions in all positions within a word, with increased reading times compared to the normal condition. However, comprehension was high and so both groups were able to successfully read the text containing TL nonwords. Therefore, as in Experiment 4, both young and older adults displayed flexible letter position coding. In Experiment 4 all words were presented correctly once the eye moved past them and during any subsequent rereading. In line with Experiment 4, contrasts revealed that for both young and older readers beginning transpositions were more disruptive than end transpositions, and end transpositions were more disruptive than internal transpositions. These findings provide further support for the notion that external letters, particularly the beginning letter, have a privileged role in word identification (e.g. Guérard et al., 2012; Johnson & Eisler, 2012; Rayner, White et al, 2006; White et al., 2008).

Crucially, in contrast to Experiment 4, age-group did not interact with the position of the transposition. In Experiment 4 the transpositions remained throughout the trial, including during rereading. As the older adults generally spent more time rereading than the young adults, they were more likely to re-encounter difficult to read TL nonwords. In contrast, in Experiment 5 a gaze-contingent manipulation was employed such that words that included letter transpositions during first-pass reading were presented correctly once the eye moved past them. Unlike in Experiment 4, the transpositions affected the eye movement behaviour of young and older adults similarly. Thus, it appears that the interaction effect between age and the word-beginning transposition condition in Experiment 4 was not due to older readers having generally greater difficulty processing words with transposed letters. Rather, as is typical during older age (e.g. Rayner, Reichle et al., 2006), the older adults were generally more likely to make regressive saccades, and therefore in Experiment 4 they were more likely to reencounter the TL nonwords. Thus, the interaction observed in Experiment 5 is likely to reflect a "double-whammy" effect of repeated exposure to TL nonwords.

4.4. General Discussion

The current study explored letter position coding in young and older adults by transposing adjacent letters within words. There are several key findings: 1) Adult age differences in reading: older adults once again displayed standard adult age differences in reading. 2) Letter position coding: both age-groups displayed flexible letter position coding. The impact of letter transpositions at different positions within words during reading was similar for young and older adults, 3) Older readers “double-whammy” effect: the more extensive rereading ordinarily undertaken by older adults can lead to larger effects of letter transpositions for measures sensitive to rereading.
These key findings and methodological implications are discussed in more detail in the following sections.

Adult age differences in reading

Effects of adult age were largely consistent with those of previous literature (e.g. Rayner, Reichle et al., 2006) in that older adults produced longer sentence reading times, more fixations, more regressive saccades, more skips, and longer progressive saccade lengths than young adults in the normal text condition in Experiment 4, with similar numerical patterns found in Experiment 5, although these did not always reach significance This pattern of age-related reading difficulty is in line with the pattern shown in Experiments 1, 2 and 3, the skipping results are also in line with Experiment 1 (for a comparison across experiments, see Appendix A).

Letter position coding

The pattern of results shown in both Experiment 4 and Experiment 5 for transpositions at different positions within words are in line with previous studies examining these processes in young adults, both in isolated word recognition and in sentence reading (Carr et al., 1976; Forster, 1976; Guérard et al., 2012; Johnson et al., 2007; Jordan et al., 2012; Rayner & Kaiser, 1975; Rayner, White et al., 2006; White et al., 2008). The finding that older adults can comprehend TL nonwords, and that they can do this with relatively little disruption to the reading process, indicates that they have flexible letter position coding. The key concern of the current study was to establish whether letter position coding processes are equivalent in young and older adults. These findings are also important for informing models of word recognition. Clearly, models that employ fixed letter position coding (e.g., Dual-Route Cascaded Model, Coltheart, et al., 2001; The Interactive-Activation Model, McClelland & Rumelhart, 1981) cannot adequately account for letter position coding processes in either young or older adults (for a description of these models, see Chapter 1, Section 1.4.3). Models of letter position coding incorporating flexibility may better account for these findings (e.g. SERIOL, Whitney, 2001; SOLAR, Davis, 1999; The Overlap Model, Gomez et al., 2008). Currently, models of eye movement control during reading (e.g. E-Z reader model; Reichle, Pollatsek, Fisher, & Rayner, 1998) do not make specific predictions concerning letter position coding (see Johnson et al., 2007). Further research is necessary to provide a link between the input coding scheme in models of visual word recognition and the when/where processes in models of eye movement control (see Chapter 6, Section 6.2).

Furthermore, transpositions of letters in both internal and external positions disrupted reading, indicating that the position of both internal and external letters is important for both young and older adults. This finding is particularly important as it reveals that despite a range of visual declines in advanced age visual crowding (Scialfa et al., 2012) and decreased sensitivity to fine visual detail (Crassini et al., 1988; Owlsey, 2011), the position of internal letters remains important for normal word recognition.

Importantly, the results also show that effects of letter position previously shown for younger adults, also hold for older adults. That is, external letters are more important than internal letters, and word beginning letters are especially important (Aschenbrenner et al., 2017; Carr et al., 1976; Forster, 1976; Guérard et al., 2012; Johnson & Eisler, 2012; Jordan et al., 2003; Rayner & Kaiser, 1975; Rayner, White et al., 2006; White et al., 2008). The increased importance for the beginning letter in comparison with the end letter supports the suggestion that perhaps these letters contribute to word recognition through different processes, such as beginning letters having greater parafoveal availability and being important for constraining lexical candidates. Johnson and Eisler's (2012) study indicated that for young adults the importance of word ending letters may be due to reduced lateral interference between letters as the end letter always followed by a space. Similar factors may well account for the importance of word ending letters for older adults, especially given older adults' sensitivity to crowding (Scialfa et al., 2012). Similar to young adults, word initial letters may be important due to constraining possible lexical candidates (e.g. Clark & O'Regan, 1999) or because the first letter has a privileged role (Gomez et al., 2008) in letter position encoding (see: Aschenbrenner et al., 2017; Johnson & Eisler, 2012).The current study extends this previous work to demonstrate that this pattern holds for readers aged 65+ years.

The indication from these results is that letter position coding in older adults is operating in a similar way to young adults, with a similar pattern of importance for beginning, internal and end letters within a word. That is, letter position coding within words appears to remain relatively intact in older age for both word internal and word external letters.

Older readers "double-whammy" effect

While older adults produced longer rereading times when words containing letter transpositions of beginning letters were present throughout reading (Experiment 4), this interactive effect was eliminated when TL nonwords were correctly spelled during subsequent rereading (Experiment 5). As has been highlighted throughout this thesis, a number of studies have reported that longer reading times for older adults are associated with more regressive eye movements and longer rereading times (e.g. Rayner, Reichle et al., 2006, see Chapter 1, Section 1.3.2). Therefore older adults are revisiting words in the text more often than young readers. A greater likelihood of rereading results in repeated processing of words that are more difficult to process (e.g. TL nonwords), therefore increasing the time spent rereading. It seems likely that the differences in rereading for the beginning TL condition seen in Experiment 4 are the result of older adults experiencing a "double-whammy" due to processing difficulty triggered by both first-pass and rereading of words with transposed letters and is not a result of a fundamental difference in early letter position coding processes between the two groups.

The results highlight the importance of examining first-pass eye movement measures and rereading measures separately to gain a fuller understanding of older adults' reading behaviour, as effects may be misinterpreted if only total reading times are inspected. Crucially, the "double-whammy" effect has important implications for the interpretation for future research. When comparing groups of readers with differential rates of regressions, then word characteristics that modulate first-pass reading may appear to have a larger effect on overall reading time and measures sensitive to rereading, simply because those words are more likely to be sampled again during rereading. In addition to studies of ageing, this may also be an important consideration for a range of groups associated with higher rates of regressions such as children (Blythe & Joseph, 2011) or poorer readers and those with dyslexia (Rayner, 1978). For some manipulations it may be difficult to differentiate the "double-whammy" effect from post-lexical processing difficulty (e.g. effects of word frequency may incur lexical processing difficulty, but also difficulties with integrating low-frequency words into sentential context (discussed further in Chapter 6, Section 6.2.3, see also Chapter 3, Experiment 2). Nevertheless, the possibility that patterns of results may be affected by repeated visual sampling of words that are difficult to process ("double-whammy") should at least be considered.

4.5 Conclusion

In conclusion the present study provides novel insight into letter position coding across the lifespan. The overall pattern of results suggest that young and older adults process letter position similarly. These results also suggest that models of letter position coding that incorporate flexibility (e.g. SERIOL, Whitney, 2001; SOLAR, Davis, 1999; The Overlap Model, Gomez et al., 2008) may best account for these processes in both young and older adults. Reading words with transposed letters does not appear to cause particular difficulties for older adults, therefore, changes in letter position coding is unlikely to be an immediate contributor to the reading difficulty experienced by this age group. This study also highlights the potential importance of the "double-whammy" when examining groups of readers with differential rates of regressions. The final two experiments in this thesis explores another aspect of early word processing (Experiments 6 & 7) and employ word neighbours to explore word misperception.

Chapter 5:

Adult age differences in word misperception

Older readers (65+ years) are thought to compensate for the greater reading difficulty they experience by employing a more risky reading strategy in which they infer the identities of upcoming words more readily than young adults (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). Research with lexical neighbours (words that differ by a single letter while the number and order of letters is preserved, e.g., *stork* & *story*) indicates that young readers frequently misperceive a word as its higher frequency neighbour (HFN) even during normal reading (Slattery, 2009). Previous research has not examined age differences in this neighbour frequency effect in natural reading but if older readers make riskier decisions about the identities of words they may be more susceptible to such effects, especially when the neighbour word is consistent with prior sentence context. Two experiments addressed this issue. In both, young and older adults read sentences containing critical words with and without a HFN, where the HFN was congruent with prior sentence context, or not. Further, Experiment 7 considered only visually-similar neighbours (e.g., *branch* & *brunch*). Consistent with previous findings for young adults, eye movements were disrupted more for words with than without an HFN when the HFN was congruent with prior context. However, age differences in this effect were found only in Experiment 7, when critical words and HFNs were visually as well as orthographically similar. These findings have important implications for understanding the nature of word misperception in older age.

5.1 Introduction

Experiments 6 and 7 examine whether older adults make more word misperception errors during reading than young adults. These experiments provide a key test of whether older adults are “risky” readers (Rayner, Reichle et al., 2006; see Chapter 1, Section 1.3.2). According to the risky reading hypothesis older adults are more likely than young adults to infer the identities of words based on prior context and only partial word information and so this may be an important difference in early word processing between young and older adults. The use of such a strategy may mean that older readers are more strongly predisposed to anticipate upcoming word identities and so skip words more frequently, thereby speeding the progress of their eyes through text. But, as they are also more likely to misidentify words, older readers make more backward eye movements to reprocess words. Despite being such a central issue, very few studies have examined the use of contextual information by older adults (e.g. Rayner, Reichle et al, 2006) and none have investigated word misperception during natural reading for older adults. Therefore, the notion that older adults are more likely to misperceive words has not been examined in detail. The current experiments aimed to address this issue using word neighbours. The following sections summarise word misperception in young adults and the use of context by older adults.

Word neighbours

Several studies with young adult participants show that even individuals with good reading abilities often misperceive words during normal reading (Gregg & Inhoff, 2016; Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999; Slattery, 2009). These errors were revealed by examining eye movements for words that have lexical neighbours, such as “*spice*” and “*space*” (Coltheart, Davelaar, Jonasson, & Besner, 1977; See Chapter 1, Section 1.4.2). Such words had already been used extensively in single word priming experiments to investigate mechanisms underlying the recognition of individual words. Both neighbourhood size (number of word neighbours) and neighbour frequency (whether a word has a higher frequency neighbour) have been found to influence processing. The current study is concerned with the recognition of words that have a higher frequency neighbour (HFN). Brief exposure to a word's HFN as a prime can slow the subsequent recognition of that word and words with a HFN elicit slower responses in lexical decision tasks (LDT) than words without a HFN (for a review, see Andrews, 1997; See also, Chapter 1, section 1.4.2). Most models of word recognition (e.g. McClelland & Rumelhart, 1981; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001, for a description of these models, see Chapter 1, Section 1.4.3) assume a spread of activation, such that exposure to a word activates not only the lexical entry for that word but also lexical entries for its neighbours, these words compete for selection, and this slows recognition. The implication of this finding is that, although the word's neighbour is never encountered, its availability in the reader's mind has the capacity to disrupt recognition. Further, there is some evidence that the nature of these effects in isolated visual word recognition change with age, although the nature of this difference has not been well established, e.g. McArthur, Sears, Scialfa and Sulsky (2015) found that older adults displayed a larger inhibitory neighbourhood frequency effect in a progressive demasking task compared to young adults, while Robert and Mathey (2007) found no inhibitory neighbourhood frequency effect for older adults in a lexical decision task. Crucially, the current study is interested in word misperception (i.e. cases where the word is mistaken for its HFN) in natural reading.

Eye movement studies using word neighbours

Research with young adults examining eye movements during sentence reading have further revealed the nature of HFN word misperception effects. Normal reading is disrupted when a sentence contains a word which has a lexical neighbour that has a higher frequency of written usage (Pollatsek et al., 1999; Slattery, 2009). Crucially, Pollatsek et al., (1999) found that the effect of encountering a HFN during natural reading emerged late in the eye movement record, after readers have left the critical word, in longer second-pass and total reading times for critical words and an increased incidence of regressions to these words. This suggests the readers were initially misidentifying the word. Indeed, according to the lexical competition account of HFN effects, words that have a higher frequency of written usage are more familiar and so have a natural advantage in this competition. Consequently, the HFN will sometimes win the lexical competition, with the result that the reader occasionally misperceives a word as its neighbour (e.g., Coltheart et al., 2001; Davis, 2003; Grainger & Jacobs, 1994, 1996). The implication of these findings is that lexical competition between the critical word and its HFN has little effect on the initial processing of words, and disruption only occurs once the misidentification is detected. Once this misperception becomes apparent, the reader will then need to correct this misperception, for example, by making a regression back to that word. In line with this, Slattery (2009) additionally showed that disruption to reading mostly occurs when the HFN is congruent with prior sentence context, indicating that word misperception is mediated by context. These findings suggest that misperception of HFNs is also a useful mechanism for examining effects of context in reading, as context plays a vital role in determining which word is identified (discussed further in the next section). There is good reason to speculate that there may be age-related differences in word misperception. Not only do older adults experience visual declines, they are also hypothesised to have a slower rate of lexical processing (Rayner, Reichle et al., 2006) and be more prone to guessing the identities of upcoming words in order to off-set the effects of this slower processing. However, to date, this has not been investigated.

Effects of ageing and context

For young adults, at least, there is considerable evidence of the importance of contextual information in determining when and where to move the eyes (e.g. Balota, Pollatsek, & Rayner, 1985; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Fitzsimmons & Drieghe, 2013; Rayner, Reichle et al., 2006; Rayner, Slattery, Drieghe, & Liversedge, 2011; Rayner & Well, 1996; Schotter, Lee, Reiderman, & Rayner, 2015; White, Rayner, & Liversedge, 2005). However, clear evidence for the greater use of context by older readers is lacking (Madden, 1988; Stine-Morrow, Miller, Gagne, & Hertzog, 2008; Federmeier & Kutas, 2005; Federmeier, Kutas, & Schul, 2010). Indeed, Rayner, Reichle et al. (2006) failed to observe larger context effects for their older than younger adults, although the greater use of context to predict word identities is a key component of risky reading.

Some previous studies have hinted at age differences in the use of predictability information. Kliegl, Grabner, Rolfs and Engbert (2004) reported that a word’s predictability affected the skipping rates (one of the key components of risky reading) of young but not older readers. More recently, Choi, Lowder, Ferreira, Swaab and

Henderson (2017) reported larger effects of predictability on critical word reading times for older than younger adults, supporting the notion that older readers make particular use of contextual information. However, these studies typically test the use of contextual information by making a critical word either predictable or unpredictable and have not considered the role of *plausibility,* i.e. how well the word "fits" within the sentence context (see Chapter 1, Section 1.4.5). Indeed, this is an important consideration, as comparing only very predictable and very unpredictable words may not give the full picture. It will therefore be important to investigate the influence of context on the misperception of words by young and older readers to gain a fuller understanding of how these effects might change with age. If older adults are using contextual information to make rapid decisions about word identities based on degraded input, this type of manipulation could reveal this. To date, no studies examining the use of context by older adults have used HFNs. The current studies aim to examine if older adults are more susceptible to misperception effects caused by the availability of a word's HFN and its congruency with prior context.

5.2 Experiment 6

Previous research has not addressed the issue of whether older adults make more word misperception errors than young adults. Further, research investigating whether older adults make greater use of sentence context to inform their reading has produced inconsistent results. Accordingly, the present experiment aimed to: 1) Examine whether young and older adults are differentially affected by reading sentences containing a critical word with a HFN. 2) Examine whether older adults make greater use of contextual information to inform their decision about the identity of the critical word.

Young and older adults read sentences that included a critical word with or without an HFN (using stimuli from Slattery, 2009). In addition, two types of context were used: neutral and biased (see Figure 5.1). In neutral contexts, both the critical word and its HFN were congruent with the prior sentence context but only the critical word was congruent with the post-target text. By comparison, in biased contexts only the critical word was congruent with the prior sentence context. The logic of this approach was that the nature of the stimuli allowed a critical word's HFN to receive bottom-up activation from its orthographically similar neighbour (i.e., the critical word), and top-down activation from the prior context in neutral sentences, whereas any top-down feedback would be inhibitory in biased sentences and so should reduce the likelihood that the word would be misidentified.

In line with previous studies (Slattery, 2009) it is anticipated that the word misperception effect will emerge late in the eye movement record. It is also expected that there will be an interaction between critical word type and context for the young adults, so that eye movements are disrupted more for critical words with than without an HFN and so that this disruption is greater in neutral than biased contexts. Crucially, the experiment will reveal if the pattern of misperception effects differs for the young and older readers. In particular, if the older adults use a more risky reading strategy, they may be more susceptible to word misperception effects and so be more disrupted than the younger readers when sentences contain a critical word with than without an HFN. In addition, if the older readers make greater use of context to anticipate word identities, they may be more likely to misidentify a critical word as its HFN, and so experience greater disruption to reading than the young adult readers, in neutral compared to biased contexts.

5.2.1 Method

Participants. Twenty-eight young adults (*M*= 20 years, range= 18-29 years, 18 female) and 28 older adults (*M*= 69 years, range= 65-77 years, 19 female) were recruited from the University of Leicester and the surrounding community. The requirements for participation were the same as in Chapters 2, 3 and 4. Compared to the young adults, the older adults had lower acuity and lower contrast sensitivity ($ps < .05$). The two groups were closely matched for years of education and all participants reported reading for at least several hours each week (these participant characteristics are summarised in Table 5.1). In addition, cognitive abilities were assessed using the Montreal Cognitive Assessment (MoCA), applying an exclusion criterion of <26/30. Working memory (forward and backward digit span) and vocabulary were assessed using the Wechsler Adult Intelligence Scale (WAIS-IV) subtests. Young and older adults produced similar mean digit span scores (young adults, *M*=21/32, range=14-26; older adults, *M*=22/32, range=17-32; $t(54)=1.83$, $p>.05$). The older adults produced higher mean vocabulary scores than the young adults, however (young adults, *M*= 44/57, range=29-55; older adults, *M*=53/57, range=43-57; $t(54)=6.50$, $p<.001$), consistent with previous indications of a vocabulary advantage for older adults (e.g., Ben-David, Erel, Goy, & Scheider, 2015; Keuleers, Stevens, Mandera, & Brysbaert, 2015).

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/19	20/14-20/25	20/26	20/17-20/35
Low contrast near acuity	20/34	20/20-20/40	20/40	20/24-20/46
High contrast distance acuity	20/19	20/14-20/25	20/26	20/20-20/35
Low contrast distance acuity	20/32	20/22-20/36	20/42	20/25-20/50
Screen distance acuity	20/18	20/14-20/25	20/25	20/17-20/35
Contrast-sensitivity	2.01	1.95-2.15	1.95	1.90-2.00
Years of education	14.8	13-19	15.8	11-22
Hours spent reading/week	10.5	5-20	11.5	4-25

Table 5.1. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 6. Appropriate correction was applied to calculate acuity at the distances used.

Materials and Design. The experiment was a 2 (age-group: young adult, older adult) x 2 (critical word type: experimental, control) x 2 (context: neutral, biased) mixed design. The critical word stimuli were 44 word pairs comprising 44 words with a HFN and 44 control words that do not have an HFN (from Slattery, 2009). Critical words were between 4 and 6 letters long and experimental and control words were matched for letter and syllable length and number of lower frequency neighbours (calculated using N-watch; Davis, 2005)(See Table 5.2).

Variable	Experimental	Control	Neighbour
Number of letters	5.1	5.0	5.1
Number of syllables	1.2	1.3	1.3
Lexical Frequency (CELEX-frequency per million)	13.02	14.10	130.00
Lexical Frequency (SUBTLEX-UK- Zipf-values)	3.75	3.82	4.97
Number of low frequency neighbours	2	2	4

Table 5.2. Critical word properties for Experiment 6.

The experimental and control words were matched for lexical frequency using the CELEX (Baayen, Piepenbrock, & Gulikers, 1995) and SUBTLEX-UK databases (van Heuven, Manderab, Keuleers, & Brysbaert, 2015; see Table 5.2; see also Chapter

1, Section 1.3.2). The experimental words were intentionally selected so that their HFN had a higher lexical frequency. Each pair of critical words was placed in two sentences frames, a neutral sentence frame and a biased sentence frame, producing a total of 88 sets of critical words and sentence frames in these combinations. The critical words never occupied the first or last position within a sentence. For neutral sentence frames, the experimental and control words, and the experimental word's HFN, fitted plausibly with the prior sentence context, but only the experimental word, and not the HFN, were compatible with the post-target text. For biased sentence frames, only the critical words (both experimental and control), and not the HFN, were compatible with either the prior sentence context or post-critical word text (see Figure 5.1 for an example stimulus). 30% of sentences were followed by a comprehension question.

Context	Stimulus type	
Neutral context	Experimental	The police knew that the *dagger* (danger) was purchased by their prime suspect.
	Control	The police knew that the *sword* was purchased by their prime suspect.
Biased context	Experimental	The murder weapon turned out to be a *dagger* (danger) from medieval times.
	Control	The murder weapon turned out to be a *sword* from medieval times.

Figure 5.1. Experiment 6. An example sentence in each condition. The critical word is shown in *italics*. The HFN is shown in parentheses. In the experiment sentences were shown on one line.

Off-line rating of the plausibility for the experimental critical words vs. their HFNs within the sentence context were collected from 12 participants (aged 18-30 years) who rated the plausibility of the critical word or their HFNs on a 5-point scale (1= the word does not fit at all, 5= the word fits completely). Following the same pattern as the norms collected by Slattery (2009) using the same stimuli with American participants, for the neutral items, a small but significant preference was found for the HFN (HFN; M= 4.86, critical word; M= 4.49; t= 2.96, p< .05). For the biased items a strong preference was found for the experimental critical word (HFN; M=1.51; critical word; M= 4.90; t= 23.49, p< .001). A Latin Square was used to counterbalance sentence presentations for each age-group so that each participant saw a sentence containing each critical word only once, but an equal number of sentences in each experiment condition, and critical words were seen equally often in neutral and biased contexts across each age-group.

Apparatus. Apparatus was the same as in previous chapters.

Procedure. Participants completed the visual and cognitive tests at the start of the session. The rest of the procedure was the same as in previous chapters.

Analyses. Following standard procedures, fixations under 80ms and over 1200ms were removed. This accounted for 2.2% of fixations. The data were analysed using linear mixed effects models (LMEM; Baayen, Davidson, & Bates, 2008). LMEMs were conducted using R (R Core Team, 2015, version 3.2.3) and the lme4 package (Bates, Maechler & Bolker, 2011, package version 1.1-12). Following current practice, a maximal random effects structure was used for continuous measures (following Barr, Levy, Scheepers & Tily, 2013) [10]. Participants and stimuli were always specified as crossed-random effects. Generalised linear models were conducted for dichotomous variables. For sentence-level analyses, only age-group was entered as a fixed effect. For critical word-level models, age-group, critical word type and context were specified as fixed factors. For all analyses, *t*/*z* values >1.96 were considered significant. Additional analyses conducted with working memory and vocabulary scored included as co-variates produced no significant effects and so analyses are reported without these variables included (although this does not rule out an effect of these variables, see Chapter 6, Section 6.3.1).

Sentence-level analyses examined: sentence reading times, average fixation duration, number of fixations, number of regressive saccades, and number of first-pass skips. Critical word-level analyses examined a range of standard measures that were informative about processing that occurred during the initial analysis of critical words and prior to a fixation to the right of these words (i.e., first-pass processing): word-skipping, first-fixation duration, single-fixation duration, gaze duration and first-pass re-fixation probability. Measures sensitive to the later processing of the critical words were

[10] If a model failed to converge, the structure was pruned until convergence was achieved. Analyses for continuous variables for both untransformed and log-transformed data produced the same patterns of results, and so only results for untransformed data are reported. Sentence-level measures for number of regressions and number of first-pass skips can include zero values, so a small amount (less than one) was added to each zero to allow log-transformation of these data.

also examined: rereading time, regressions-in, and total reading time (as defined in Chapter 1, Section 1.3.4). All participants achieved a high level of comprehension accuracy in all conditions (Min= 80%) and this did not vary across conditions or age-group (*ps*>.05).

5.2.2 Results

Sentence-Level Analyses. Sentence-level analyses considered only overall age differences across conditions. Means and standard errors are displayed in Table 5.3. The young and older adults did not differ in sentence reading times, average fixation duration, number of fixations, or number of regressive saccades (all $t/z<1$), but, older adults skipped more words during first-pass reading than young adults (β= 0.64, SE= 0.25, t= 2.52). Therefore, in these sentence-level measures there was no indication of age-related reading difficulty, but the skipping results are suggestive of more risky reading. For a comparison to the other experiments in this thesis see Appendix A.

Measure	Age-Group	
	Young	Older
Sentence reading time (ms)	3196 (220)	3154 (242)
Fixation duration (ms)	257 (7)	254 (7)
Number of fixations	11.8 (0.7)	12.3 (0.7)
Number of regressive saccades	2.5 (0.4)	2.6 (0.4)
Number of first-pass skips	4.2 (0.4)	4.8 (0.4)

Table 5.3. Experiment 6. Means for sentence-level measures. The Standard Error of the Mean is shown in parentheses.

Critical word analyses. Means and standard errors for these measures are shown in Table 5.4, LMEM statistics are summarised in Table 5.5. Figures displaying key results can be found in Figure 5.2-5.4. In the 2 (age-group: young adult, older adult) x 2 (critical word type: experimental, control) x 2 (context: neutral, biased) analyses there was no significant main effect of age for first-fixation duration, single-fixation duration, gaze duration, rereading time or total reading time. But, compared to the young adults, the older adults skipped the critical words more often, made fewer first-pass re-fixations and made more regressions-in. Therefore, in line with the sentence-level findings, the older adults showed little indication of age-related reading difficulty but skipped words more often and also made more regressions back to the critical word compared to the young adults and so showed evidence of more risky reading.

Main effects of critical word type were obtained in total reading time, regressions-in, and rereading times. These effects were due to more regressions, and longer reading (Figure 5.3) and rereading times for words with than without an HFN. No main effects of critical word type were observed in word-skipping, first-fixation duration, single-fixation duration, gaze duration (Figure 5.2), or first-pass re-fixation probabilities. The availability of a HFN therefore did not affect the first-pass processing of critical words but influenced later processing by increasing the probability of a regression back to the critical words and the subsequent rereading of these words. This also resulted in an increase in the total reading times for the words. This pattern of effects is consistent with readers initially misperceiving a critical word as its HFN and re-processing the word following this initial misanalysis. Crucially, this effect of critical word type was observed both for young and older adults and did not interact with age, and so it appears that word misperception effects were similar for both age-groups.

An interaction between critical word type and context was obtained in total reading times, and rereading times, but no other measures (Figures 5.3 and 5.4). For both total reading times and rereading times, this interaction was due to larger increases in reading times for words with than without an HFN in neutral compared to biased contexts. The critical word's HFN always fitted plausibly with the prior sentence text in neutral but not biased contexts and was incongruent with the post-critical word text in both contexts. Critical words were therefore more likely to be misperceived as an HFN when this analysis was congruent with prior context and disruption to processing occurred once this analysis proved to be incongruent with the post-critical word context. This mediation of the word misperception effect by the congruency of the HFN with context is consistent with previous findings (Slattery, 2009). Crucially, however, there was no three-way interaction between critical word type, context and age-group, and so no indication that this influence of context differed for young and older adults. Rather, it appears that young and older adults made similar use of context to guide their initial processing of words. Indeed, the very clear finding from the present research is that both young and older adults often misperceive a word as its lexical neighbour and that context has a rapid influence on these lexical processing decisions during reading for both age-groups.

Measure		Neutral Context		Biased Context	
		Experimental	Control	Experimental	Control
First-fixation duration (ms)	Young	234(13)	235 (14)	236 (13)	237 (15)
	Older	245(14)	244 (13)	241 (13)	254 (16)
Single-fixation duration (ms)	Young	238(13)	239(14)	245(13)	242(14)
	Older	251(13)	248(13)	24713)	260(15)
First-pass refixation Probability	Young	.17 (0.2)	.17 (0.2)	.15 (0.2)	.15 (0.2)
	Older	.09 (0.1)	.07 (0.1)	.10 (0.2)	.09 (0.2)
gaze duration (ms)	Young	269 (21)	270 (20)	266 (20)	268 (20)
	Older	258 (14)	258 (17)	260 (14)	271 (20)
Proportion of regressions-in	Young	.30 (0.2)	.23 (0.2)	.21 (0.2)	.18 (0.2)
	Older	.39 (0.2)	.35 (0.2)	.29 (0.2)	.24 (0.2)
Rereading time (ms)	Young	136 (9)	106 (9)	92 (8)	74 (7)
	Older	180 (11)	143 (9)	115 (9)	113 (9)
Total reading time (ms)	Young	394 (19)	368 (18)	348 (16)	338 (17)
	Older	400 (27)	363 (26)	345 (23)	350(24)
Proportion of words skipped	Young	.16(0.2)	.14 (0.2)	.17 (0.2)	.18 (0.2)
	Older	.23 (0.2)	.24 (0.2)	.24 (0.2)	.23 (0.2)

Table 5.4. Experiment 6. Means (and standard errors) for young and older adults in each condition.

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	First-Pass Refixation Probability	Gaze Duration (ms)	Proportion of Regressions-in	Rereading Time (ms)	Total Reading Time (ms)	Proportion of words skipped
Intercept	***β***	240.44	248.67	2.35	264.14	1.12	117.67	362.13	1.59
	SE	4.60	5.02	0.14	6.02	0.10	10.64	13.06	0.11
	t/z	52.26*	49.57*	16.78*	43.89*	11.33*	11.06*	27.74*	14.40*
Age									
Young vs. Older	***β***	9.98	9.41	0.77	4.50	0.45	35.14	4.66	0.48
	SE	8.96	9.59	0.26	11.31	0.17	19.14	23.11	0.20
	t/z	1.11	0.99	3.02*	0.40	2.65*	1.84	0.20	2.45*
Critical Word Type									
Experimental vs.	***β***	3.32	1.94	0.07	2.94	0.26	20.08	14.69	0.05
Control	***SE***	2.75	2.71	0.11	3.29	0.07	5.93	6.20	0.08
	t/z	1.21	0.72	0.62	0.89	3.43*	3.39*	2.37*	0.66
Context									
Neutral vs. Biased	***β***	1.84	3.33	0.02	2.32	0.48	42.93	34.22	0.10
	SE	3.12	4.00	0.14	5.67	0.12	11.01	13.65	0.13
	t/z	0.59	0.83	0.18	0.41	3.94*	3.89*	2.51*	0.82
Age x Critical Word Type									
Young vs. Older X	***β***	4.13	4.22	0.22	2.74	0.09	5.12	7.06	0.08
Experimental vs.	***SE***	4.39	5.42	0.21	5.74	0.15	11.85	12.40	0.15
Control	**t/z**	0.94	0.78	1.03	0.48	0.63	0.43	0.57	0.49
Age x. Context									
Young vs. Older X	***β***	0.50	4.22	0.33	7.79	0.09	10.95	9.60	0.16
Neutral vs. Biased	***SE***	4.66	5.42	0.21	7.79	0.15	11.87	12.42	0.15
	t/z	0.11	0.27	1.55	1.00	0.63	0.92	0.77	1.06

Table 5.5 Experiment 6 LMEM statistics. Significant effects are indicated by an asterisk (*). Table continued on next page

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	First-Pass Refixation Probability	Gaze Duration (ms)	Proportion of Regressions-in	Rereading Time (ms)	Total Reading Time (ms)	Proportion of Words Skipped
Critical Word Type x Context									
Experimental vs. Control X Neutral vs. Biased	***β***	8.10	1.47	0.06	7.03	0.08	23.20	34.50	0.04
	SE	6.08	5.42	0.21	7.31	0.15	11.86	12.41	0.15
	t/z	1.33	1.16	0.30	0.96	0.53	2.04*	2.78*	0.26
Age x Critical Word Type x Context									
Age X Experimental vs. Control X Neutral vs. Biased	***β***	12.27	16.62	0.02	9.59	0.34	25.19	37.24	0.31
	SE	10.17	10.82	0.42	13.12	0.29	23.71	24.80	0.31
	t/z	1.21	1.44	0.05	0.73	1.18	1.06	1.20	1.01

Table 5.5 continued.

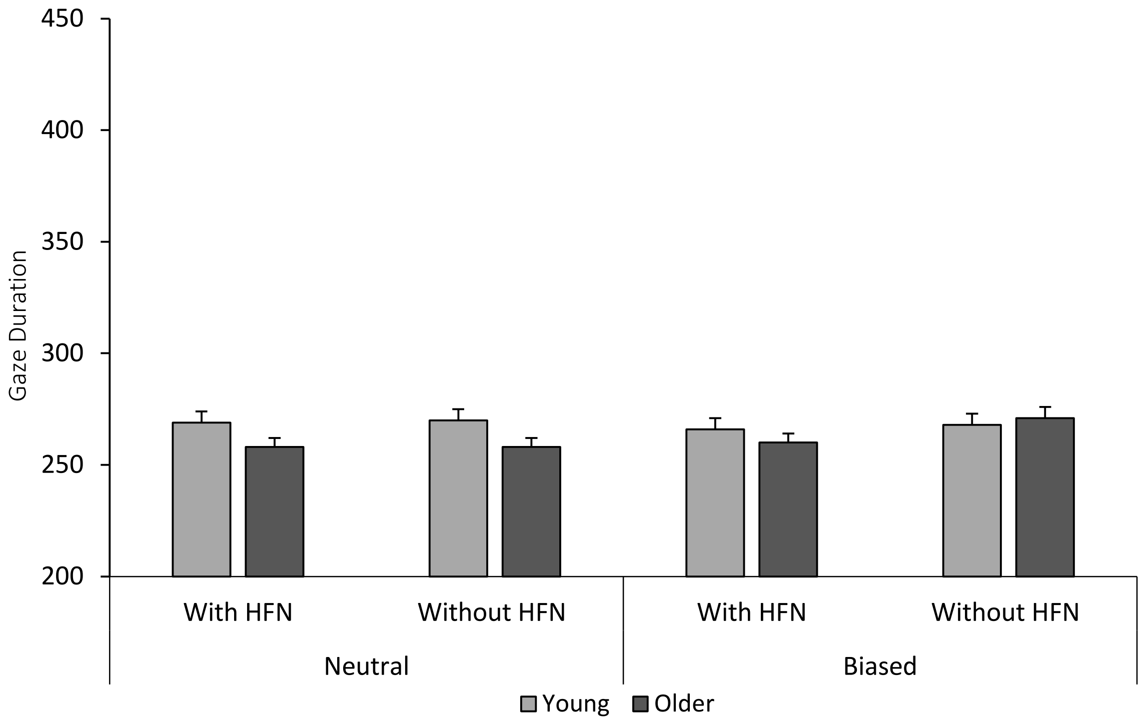

Figure 5.2 Experiment 6. Mean gaze durations for young and older adults in each condition. Error bars correspond to one standard error.

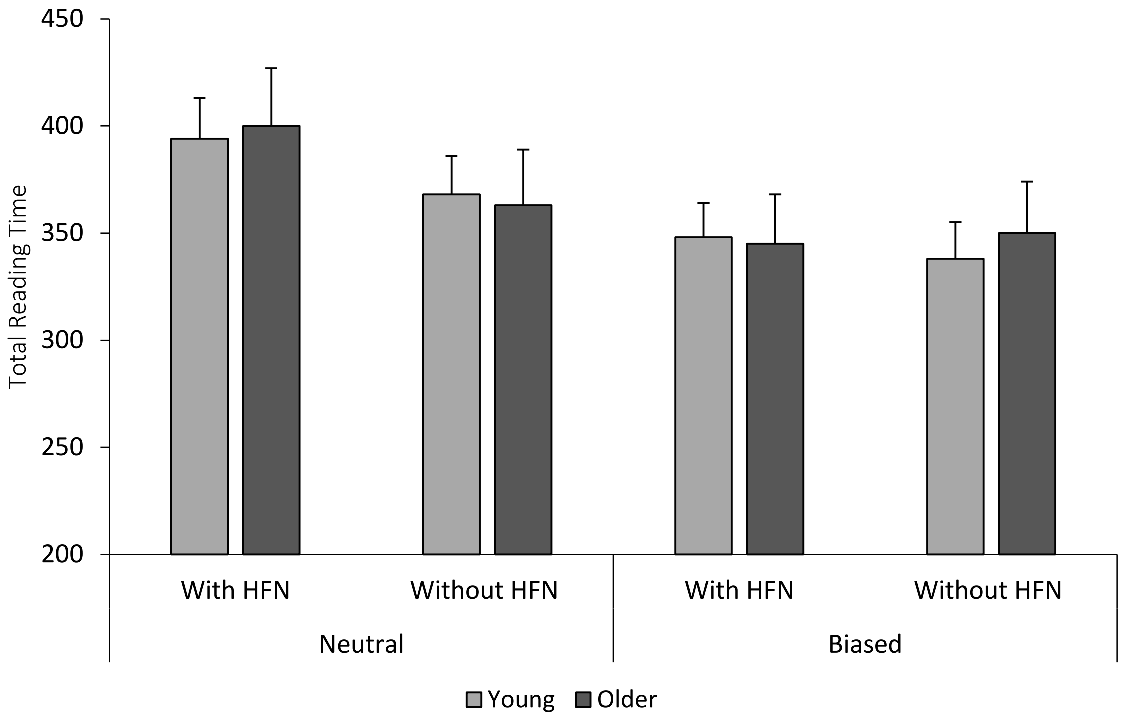

Figure 5.3. Experiment 6. Mean total reading times for young and older adults in each condition. Error bars correspond to one standard error.

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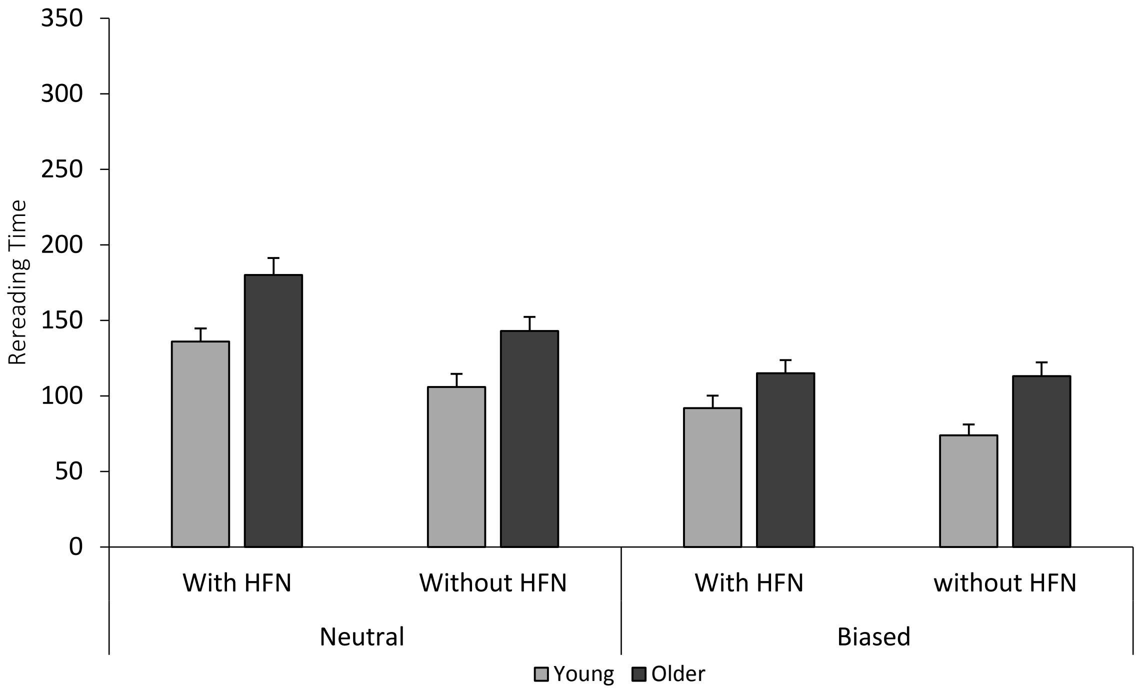

Figure 5.4. Experiment 6. Mean rereading time for young and older adults in each condition. Error bars correspond to one standard error.

In addition to the LMEM analyses, Bayes Factors (Kass & Raftery, 1995) were also computed for each measure in order to examine how strong the evidence is in favour of the null-hypothesis. This analysis focuses mainly on interactive effects, as these are the key effects of interest. Bayes Factors were computed using the BayesFactor package (Rouder, Morey, Speckman & Province, 2012) in R (R Core Team, 2015). Marginal likelihood was obtained using Monte Carlo sampling, with iterations set at 100,000. The scaling factor for g-priors was set at 0.5.

For gaze duration, the analysis favoured a null model (all BF= < 1.00), suggesting that single fixation durations were not influenced by any of the experimental variables. For first fixation duration and gaze duration the analysis favoured a model containing only a main effect of age (BF= 195, and 7.51, respectively). This suggests that some subtle adult age differences are present and also supports the conclusion of the LMEM analyses that misreading a word as its HFN has a relatively late impact on eye movement behaviour. A model with a main effect of age was also preferred for refixation probability and word skipping (BF=6.87×10^{8} and 9.63×10^{6}).

For the likelihood of a regression-in to the critical word, the analysis preferred a model containing main effects age, word-type and context, but no interactions (9.33×10^{15}). Crucially, for the measures total time and rereading time, of all model variations, the highest Bayes Factor was obtained for a model containing main effects of word type, context and a context x word type interaction for total time (BF=6095.81), and a model containing all three main effects, plus a word type x context interaction for rereading time (BF=1.52×10^{13}). On the other hand, the Bayes Factor associated with the full model for total time was 0.20. This value well below one indicates that the likelihood of these results is greater under a null model than under one that assumes main effects and a three-way interaction. For rereading time, weak support for a full model over the null model was found (BF= 4.81), however a direct comparison of the full model against the most preferred model found no support for the full model (BF= < 0.001). Therefore, the data may be regarded as substantially more likely under the simpler model, supporting the conclusions of the main analyses that age does not influence the word misperception effect.

5.2.3 Discussion

Experiment 6 demonstrated clear word misperception effects during normal sentence reading, such that readers sometimes misread a word as its HFN, particularly when the HFN was congruent with the prior sentence context. The findings also showed that misreading a word as its HFN has a relatively late impact on eye movement behaviour, and this was observed in rereading and total reading times for the critical words and the incidence of regressions back to these words, but not measures sensitive to the early processing of these words. The indication, therefore, is that disruption to eye movements follows the detection of a misanalysis, typically when the misread word becomes incongruent with subsequent text and may reflect efforts to repair this misanalysis by reprocessing the misread word. These findings are in line with findings from previous investigations of word misperception (Slattery, 2009).

The Experiment 6 aimed to extend previous findings by establishing whether the effects of word misperception are greater for older readers as a result of age-related changes in visual and lexical processing and the use of a risky reading strategy. Crucially, contrary to expectation, older readers were disrupted to a similar extent by the availability of a word's HFN and showed very similar influences of context to the younger readers. The indication, therefore, is that older readers show standard effects of word misperception and sentence context. The current results appear contrary to the view that older readers take a more risky approach to lexical identification, according to which they are more likely to "guess" the identities of words based on only partial word information and are more reliant on context to guide these decisions. However, it was also of interest that Experiment 6 failed to obtain clear evidence for age-related reading difficulty as reported in previous studies (e.g., Rayner, Reichle et al., 2006) and in other experiments in this thesis (see Appendix A). In particular, there were no reliable age differences in reading times, number of fixations, or average length of fixations. However, older readers did skip the critical words more frequently, made fewer refixations on these words, and were more likely to regress back to the critical words than the young adult readers. The skipping effects were of particular importance as they suggest that, despite the lack of evidence for age-related reading difficulty, the older readers' eye movement behaviour was characteristic of more risky reading.

One possibility is that the older participants in Experiment 6 were drawn from a population of more able older readers who were able to use this risky reading strategy to read as effectively as the young adults and avoid misperceiving words. Indeed, it was noteworthy that the older adults in this study outperformed the young adults on the vocabulary test (Brysbaert, Stevens, Mandera & Keuleers, 2016) and this superior vocabulary may be protective against the effects of ageing on reading performance. The older adults also demonstrated comparable performance to young adults on a digit span test. It will therefore be important for future research to establish whether less capable older readers show greater susceptibility to word misperception effects and to establish which factors are predictive of such errors (see also, Chapter 6, Section 1.3.1).

Further, the nature of the HFN stimuli used may not be ideal for capturing the types of word misperception errors that older readers may be prone to. Notably, while the critical word and its HFN differed by the substitution of only a single letter, this substitution did not necessarily preserve word shape and so a critical word and its HFN could be visually dissimilar (e.g., *story* and *stork*). Indeed, fewer than half of the HFNs in Experiment 6 preserved the shape of the critical word. However, words which are visually, as well as orthographically similar to one another may be especially confusable for older readers due to visual declines in older age (for a review, see Owsley, 2011). Indeed, because older adults have lower acuity and reduced sensitivity to visual detail, especially outside of central vision (e.g., Crassini, Brown, & Bowman, 1988) they may have particular difficulty discriminating between visually similar words. Consequently, it is important to investigate other forms of word misperception, including errors in which a word is misidentified for a visually similar HFN (e.g., misidentifying *brunch* as *branch*). This possibility is explored in detail in Experiment 7.

5.3 Experiment 7

Contrary to expectation, Experiment 6 did not find evidence that older adults make more word misperception errors than young adults. However, in order to fully explore word misperception, it will be important to disentangle sensory and cognitive influences on the misperception of words by older readers. Indeed, because older adults have lower acuity and reduced sensitive to visual detail, especially outside of central vision (e.g., Crassini et al., 1988) they may have particular difficulty discriminating between visually similar upcoming words, As a result, older adults may rely more heavily than young adults on coarse-scale cues such as the length and shape of words (e.g., Jordan et al., 2014) to determine the identity of a word. Consequently, if older readers utilise impoverished parafoveal input when identifying a word, they may be especially likely to make errors of this nature, especially when the misperception is congruent with context. Therefore, the type of misperception errors that older adults make may not be driven (or not solely driven) by lexical competition from a word's orthographic neighbours, but also earlier visual processing (see also, Williams, Perea, Pollatsek, & Rayner, 2006).

Currently the majority of models of visual word recognition (e.g. the Interactive Activation model; McClelland & Rumelhart, 1981; the Dual-route Cascaded model Coltheart, Rastle, Perry, Langdon, & Zieglar, 2001, for a description, see Chapter 1, Section 1.4.3) do not specify a role for visual similarity in lexical access, such that overall word shape should not affect identification. However, studies suggest that visual similarity plays an important role in word recognition. In a masked priming lexical decision task, Marcet and Perea (2017a) substituted a single letter in a word for either a similar letter or a dissimilar letter. They found that similar letter primes produced faster word identification times than dissimilar-letter primes. In a further study Marcet and Perea (in press), found this effect extends to multi-letter homoglyphs (*presiclent*; cl– d), (but see Perea & Panadero, 2014). These results suggest that visual factors such as word shape, in addition to lexical factors such as word frequency, influence word identification and therefore may also play an important role in word misperception effects. Accordingly, Experiment 7 aimed to examine whether older adults make more word misperception errors than young adults when reading sentences containing a critical word with a HFN which is visually, as well as orthographically similar to the critical word. Experiment 7 also further explores whether sentence context mediates this effect.

5.3.1 Method

Participants. Twenty-eight young adults (*M*= 21 years, range= 18-27 years, 19 female) and 28 older adults (*M*= 71 years, range= 65-85 years, 17 female) were recruited from the University of Leicester and the surrounding community. The requirements for participation were the same as in previous experiments. None of these participants took part in Experiment 6. As in Experiment 6, compared to the young adults, the older adults had lower acuity and lower contrast sensitivity (*p*s< .05). The two groups were closely matched for years of education and all participants reported reading for at least several hours each week (summarised in Table 5.6). Cognitive abilities were again assessed using the MoCA test, applying an exclusion criterion of <26/30. As in Experiment 6, working memory (forward and backward digit span) and vocabulary were assessed using the WAIS-IV. Young and older adults produced similar mean digit span scores (young adults, *M*= 21/32, range=14-26; older adults, *M*= 20/32, range= 13-30; $t(54)=1.50$, $p>.05$). As in Experiment 6, the older adults produced higher mean vocabulary scores than the young adults, (young adults, *M*= 45/57, range= 30-54; older adults, *M*= 52/57, range= 38-57); $t(54)=4.86$, $p<.001$).

	Young		Older	
	Mean	Range	Mean	Range
High contrast near acuity	20/19	20/14-20/25	20/26	20/17-20/35
Low contrast near acuity	20/34	20/20-20/40	20/40	20/24-20/46
High contrast distance acuity	20/19	20/14-20/25	20/26	20/20-20/35
Low contrast distance acuity	20/32	20/22-20/36	20/42	20/25-20/50
Screen distance acuity	20/18	20/14-20/25	20/25	20/17-20/35
Contrast-sensitivity	2.01	1.95-2.15	1.95	1.90-2.00
Years of education	14.8	13-19	15.8	11-22
Hours spent reading/week	10.5	5-20	11.5	4-25

Table 5.6. Visual abilities, years of education, and hours spent reading for young and older adults in Experiment 7. Appropriate correction was applied to calculate acuity at the distances used.

Materials and Design. The general experimental design was the same as Experiment 6. Critical words and HFNs were always visually similar. Stimuli form Experiment 6 which met this criterion were retained, and additional stimuli were created resulting in 44 word pairs comprising 44 words with a HFN and 44 control words that do not have an HFN. Stimuli are listed in Appendix E. Critical words met the same requirements as the stimuli in Experiment 6, and so critical words were between 4 and 6 letters long and experimental and control words were matched for letter and syllable length (see Table 5.7). The experimental and control words were matched for lexical frequency using the CELEX (Baayen et al., 1995) and SUBTLEX-UK databases (van Heuven et al., 2015; see Table 5.7) and for number of lower frequency neighbours (calculated using N-Watch; Davis, 2005).

Variable	Experimental	Control	Neighbour
Number of letters	4.7	4.7	4.7
Number of syllables	1.2	1.2	1.2
Lexical Frequency (CELEX- frequency per million)	10.64	13.44	160.65
Lexical Frequency (SUBTLEX-UK- Zipf-values)	3.76	3.96	4.99
Number of low frequency neighbours	2	2	4

Table 5.7. Experiment 7. Critical word characteristics.

The stimuli were structured in the same way as in Experiment 6 (see Figure 5.5). Off-line ratings of the plausibility for the experimental targets vs. their HFNs within the sentence context were collected from 12 participants (aged 18-30 years) who rated the plausibility of the targets or their HFNs on a 5-point scale. Following the same pattern as the norms collected for Experiment 6, for the neutral items, a small but significant preference was found for the HFN (HFN; M= 4.58, critical word; M= 4.24; t= 2.89, p< .05). For the biased items a strong preference was found for the experimental targets (HFN; M= 1.80, critical word; M= 4.51; t= 15.21, p<.001).

Context	Stimulus type	
Neutral context	Experimental	Due to the freezing rain, the *brunch* (branch) was postponed a week.
	Control	Due to the freezing rain, the *buffet* was postponed a week.
Biased context	Experimental	Everyone said that the food at the *brunch* (branch) was simply magnificent.
	Control	Everyone said that the food at the *buffet* was simply magnificent.

Figure 5.5. Experiment 7. An example sentence in each condition. The critical word is shown in italics. The HFN is shown in parentheses. In the experiment sentences were shown on one line.

Apparatus. Apparatus was the same as in previous Experiments.

Procedure & Analyses. The general procedure, measures and analyses were the same as for Experiment 6. Additional analyses conducted with working memory and vocabulary scored included as co-variates produced no significant effects and so analyses are reported without these variables included. Fixations under 80ms and over 1,200ms were removed (2% of fixations). All participants achieved a high level of comprehension accuracy in the experiment (Min= 85%) and this did not differ by condition or age-group (*p*s>.05).

5.3.2 Results

Sentence-Level Analyses. Sentence-level analyses considered only overall age differences across conditions. Means and standard errors are shown in Table 5.8. Older adults produced longer sentence reading times, made more fixations, more regressive saccades and skipped more words during first-pass reading than young adults (all $t/z>2$). However, fixation durations were similar across the two age groups ($\beta = 1.11$, SE= 6.06, $t = 0.18$). Therefore, in line with Experiment 6, older adults showed evidence of more risky reading, however, in contrast to Experiment 6, the older adults in Experiment 7 also showed evidence of greater reading difficulty than young adults.

Measure	Age-Group	
	Young	Older
Sentence reading time (ms)	2648 (133)	3008 (170)
Fixation duration (ms)	249 (4)	250 (4)
Number of fixations	10.5 (0.5)	11.5 (0.6)
Number of regressive saccades	2.5 (0.2)	3.4 (0.2)
Number of first-pass skips	4.2 (0.2)	4.8 (0.2)

Table 5.8. Experiment 7. Sentence-level means. Standard errors are shown in parentheses.

Critical word analyses. Means and standard errors for sentence level eye movement measures are shown in Table 5.9, LMEM statistics are summarised in Table 5.10. Graphs displaying key measures can be found in Figures 5.6-5.8. In the 2 (age- young, older) x 2 (context- neutral, biased) x 2 (neighbour- with HFN, without HFN) there was a significant main effect of age for total time, regressions-in, rereading time and word skipping such that older adults produced longer reading and rereading times, skipped the critical word more often and made more regressions back to the critical word than young adults. Further, the main effect of age approached significance in total reading time. However, single-fixation durations, first-fixation durations and gaze durations did not differ significantly across age-groups. Both groups were also equally likely to make a first-pass refixation on the critical word. Therefore, in line with the sentence-level findings, the older adults showed clear evidence of greater reading difficulty and of more risky reading than young adults (for a comparison to the other experiments in this thesis, see Appendix A).

Main effects of critical word type were obtained for regressions-in and word skipping. This main effect approached significance in total reading times. In line with Experiment 6, these effects were due to more regressions, more skips and longer reading times (see Figure 5.7) for words with than without an HFN. Unlike Experiment 6, main effects of critical word type were not observed for rereading time although the same numerical pattern was present. This may be due to the lack of a misperception effect in the biased condition reducing the overall effect (described below, see Figure 5.8). Overall, this pattern of effects is again consistent with readers initially misperceiving a critical word as its visually similar HFN and re-processing the word following this initial misanalysis. The increased word skipping suggests that readers may be more inclined to guess the identity of a word with a HFN and so not fixate it during first-pass reading. Further, in contrast to Experiment 6, target type and age interacted in total reading time such that older adults reading times were particularly long when reading words with a visually similar HFN, suggesting that the older adults may have misperceived these words more often than young adults (Figure 5.7).

An interaction between critical word type and context was obtained in total reading times and rereading times (Figures 5.7 and 5.8). This interaction also approached significance for regressions-in. As in Experiment 6, this interaction was due to larger increases in reading times for words with than without a HFN in neutral compared to biased contexts, in line with Slattery (2009). Crucially, in contrast to Experiment 6 these effects further interacted with age, such that when words with a visually similar HFN were shown in a neutral context, the word misperception effect was larger for older adults (although this interaction did not reach significance for regressions-in). Therefore, older adults may be more likely than young adults to misperceive a critical word as its visually similar HFN when that HFN is congruent with prior sentence context[11].

[11] Additional Bayes Factors analyses also supported a model containing a three-way interaction for these measures.

Measure		Neutral Context		Biased Context	
		Experimental	Control	Experimental	Control
First-fixation duration (ms)	Young	238 (6)	242 (6)	243 (5)	236 (6)
	Older	250 (7)	247 (6)	247 (6)	244 (6)
Single-fixation duration (ms)	Young	247 (6)	241 (6)	242 (7)	238 (5)
	Older	250 (7)	250 (6)	248 (6)	247 (7)
First-Pass refixation probability	Young	.10 (.01)	.11 (.01)	.12 (.01)	.09(.01)
	Older	.09 (.01)	.08 (.01)	.09(.01)	.08(.01)
Gaze duration (ms)	Young	261(8)	258 (5)	264 (6)	244 (6)
	Older	269 (11)	264 (7)	262 (7)	259 (8)
Proportion of regressions-in	Young	.24(.03)	.17(.02)	.16(.02)	.14(.02)
	Older	.36(.04)	.25(.03)	.26(.02)	.25(.02)
Rereading time (ms)	Young	102 (10)	83 (8)	72 (9)	63 (8)
	Older	168 (21)	119 (15)	92 (19)	102 (21)
Total reading time (ms)	Young	345 (21)	322 (15)	314 (15)	300 (14)
	Older	402 (23)	362 (20)	334 (21)	347 (16)
Proportion of words skipped	Young	.19 (0.2)	.18 (0.2)	.19 (0.2)	.17 (0.2)
	Older	.27 (0.2)	.21 (0.2)	.26 (0.2)	.24 (0.2)

Table 5.9. Experiment 7. Means for young and older adults in each condition. Standard errors are shown in parentheses.

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	First-Pass Refixation Probability	Gaze Duration (ms)	Proportion of Regressions-in	Rereading Time (ms)	Total Reading Time (ms)	Proportion of words skipped
Intercept	***β***	242.26	244.23	2.52	261.07	1.38	101.12	338.99	1.44
	SE	4.19	4.33	0.11	5.32	0.11	10.12	11.68	0.10
	t/z	57.81*	56.35*	22.57*	49.08*	12.40*	10.00*	29.02*	14.05*
Age									
Young vs. Older	***β***	9.04	8.80	0.26	7.57	0.71	37.77	42.17	0.43
	SE	7.87	8.09	0.21	10.10	0.20	19.01	21.93	0.19
	t/z	1.15	1.09	1.24	0.75	3.53*	1.99*	1.96*	2.26*
Critical Word Type									
Experimental vs.	***β***	5.30	3.38	0.10	6.53	0.23	6.33	9.64	0.19
Control	***SE***	2.86	3.29	0.11	4.29	0.08	5.24	5.51	0.09
	t/z	1.36	1.03	0.94	1.22	2.92*	1.21	1.85	2.01*
Context									
Neutral vs. Biased	***β***	3.88	4.18	0.07	6.98	0.44	31.07	34.76	0.01
	SE	3.82	4.08	0.12	5.03	0.12	8.69	9.76	0.12
	t/z	1.02	1.02	0.59	1.39	3.63*	3.58*	3.56*	0.12
Age x Critical Word Type									
Young vs. Older X	***β***	4.79	8.06	0.01	12.42	0.07	16.83	19.13	0.11
Experimental vs.	***SE***	5.06	5.96	0.22	7.01	0.16	10.46	11.00	0.16
Control	**t/z**	0.95	1.35	0.01	1.07	0.46	1.84	2.04	1.27
Age x. Context									
Young vs. Older X	***β***	0.46	5.68	0.09	1.43	0.07	16.83	11.88	0.18
Neutral vs. Biased	***SE***	5.01	5.31	0.21	7.51	0.16	10.46	10.99	0.15
	t/z	0.09	1.07	0.44	0.19	0.44	1.61	1.08	1.30

Table 5.10. Experiment 7. LMEM statistics. Significant effects are indicated with an asterisk (*). Table continued on next page.

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	First-Pass Refixation Probability	Gaze Duration (ms)	Proportion of Regressions-in	Rereading Time (ms)	Total Reading Time (ms)	Proportion of words skipped
Critical Word Type x Context									
Experimental vs. Control X Neutral vs. Biased	***β***	2.66	4.14	0.37	6.53	0.30	33.59	32.45	0.04
	SE	5.91	6.03	0.21	8.72	0.16	10.46	10.99	0.18
	t/z	0.45	0.69	0.70	0.75	1.78	3.21*	2.95*	0.20
Age x Critical Word Type x Context									
Age X Experimental vs. Control X Neutral vs. Biased	***β***	7.71	0.06	0.56	19.85	0.23	37.10	52.91	0.22
	SE	10.56	10.71	0.43	12.39	0.31	20.93	21.98	0.31
	t/z	0.73	0.01	1.03	1.08	1.65	1.97*	2.41*	0.72

Table5.10 continued.

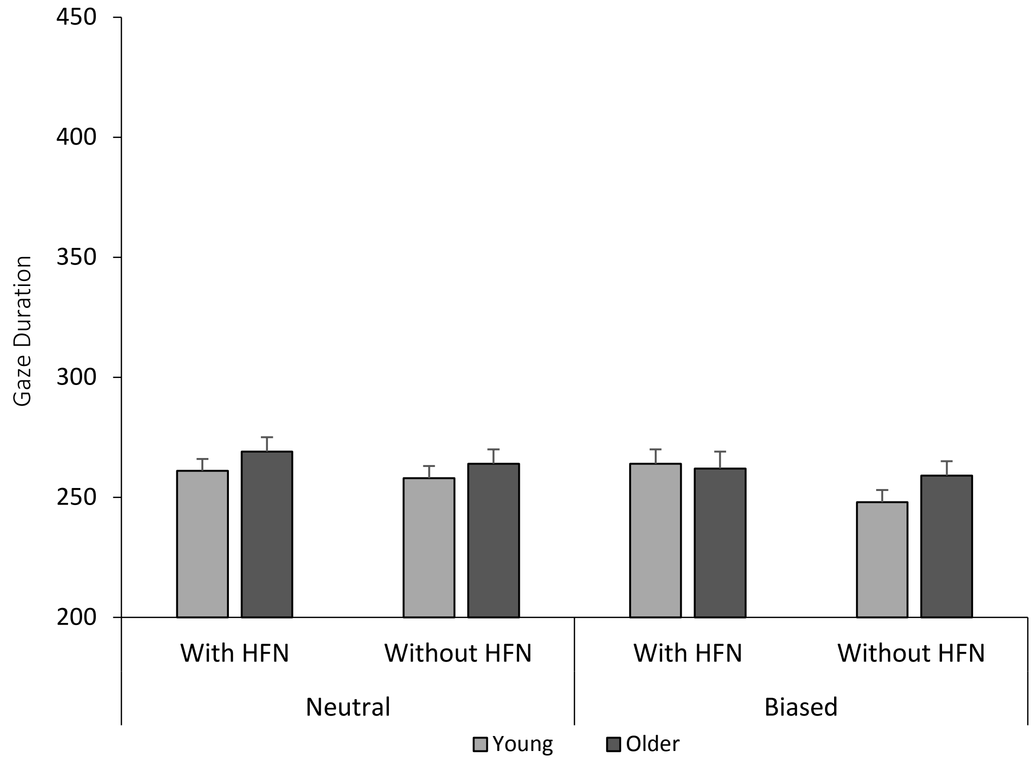

Figure 5.6. Experiment 7. Mean gaze durations for young and older adults in each condition. Error bars correspond to one standard error.

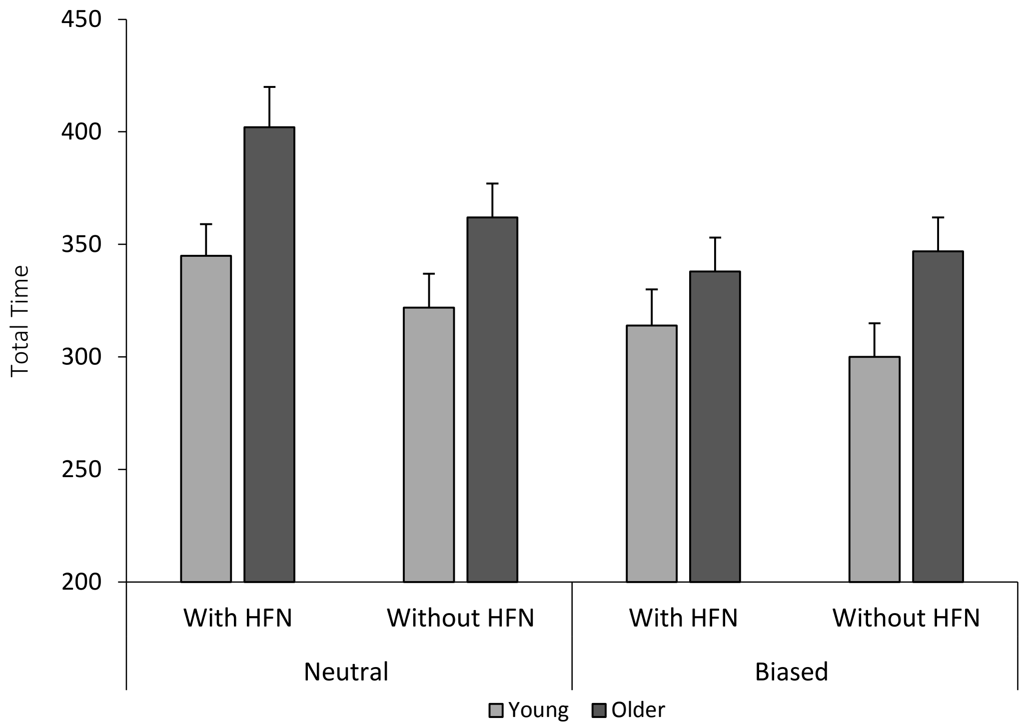

Figure 5.7. Experiment 7. Mean total reading times for young and older adults in each condition, Error bars correspond to one standard error.

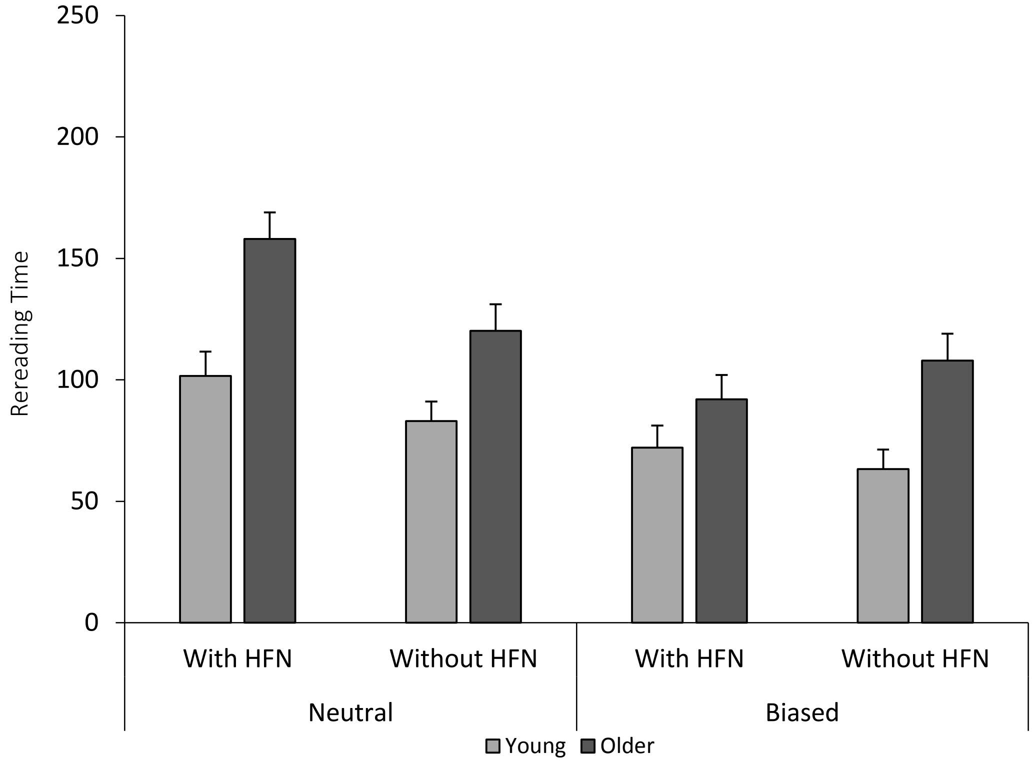

Figure 5.8. Experiment 7. Mean rereading times for young and older adults in each condition, Error bars correspond to one standard error.

5.3.3 Discussion

In line with Experiment 6, Experiment 7 demonstrated clear word misperception effects during normal sentence reading, such that readers sometimes misread a word as its HFN, particularly when the HFN was congruent with the prior sentence context. This again had a late impact on eye movement behaviour, indicating that disruption to eye movements follows the detection of a misanalysis. Building on previous HFN studies (e.g. Slattery, 2009) these results provide evidence for a visual component, as well as a lexical component, in HFN word misperception effects.

Similar to Experiment 6, older adults outperformed the young adults on a standardised test of vocabulary knowledge and demonstrated comparable working memory performance. Further, older readers skipped the critical words more frequently, and were more likely to regress back to the critical words than the young adult readers. These results are in line with previous studies suggesting that older adults may be riskier readers (e.g. Rayner, Reichle et al., 2006). However, unlike the older adults in Experiment 6, the older readers in Experiment 7 experienced greater reading difficulty than the young adults and produced longer overall reading times and made more fixations (for a comparison with other experiments in this thesis, see Appendix A).

Crucially, in Experiment 6, when critical words and HFNs could be either visually similar or visually dissimilar, there was no evidence of older adults making more word misperception errors than young adults[12]. However, in Experiment 7, when all critical words and HFNs were visually similar, older adults produced a greater increase in reading and rereading times than young adults when reading a critical word with a visually similar neighbour in a neutral context. This suggests that older adults may indeed be more likely to misperceive certain types of words than young adults, and

[12] One possibility is that the older readers in Experiment 6 were drawn from a population of more able older readers who were able to use this more risky reading strategy to read as effectively as the young adults and to avoid misperceiving words, whereas the older adults in Experiment 7 were less effective, and so were more prone to errors. To examine the possibility that the difference in results across these two studies may reflect differences in the participant group, items from Experiment 6 were divided into visually similar and visually dissimilar, and results were examined separately. As the resulting item number in each group was low, no significant effects were anticipated, and so only a visual inspection was undertaken. The numerical patterns found in Experiment 6 also pointed to a larger word misperception effect for older adults when critical words and HFNs were visually similar. This suggests that the difference across the two studies does not simply reflect differences in participant ability. These values are tabulated in Appendix F.

further that they make particular use of sentence context to inform their decision regarding word identity. However, this greater word misperception appears to be limited to cases where the HFN is visually, as well as orthographically, similar to the critical word.

5.4 General discussion

The current study explored adult age differences in word misperception and the use of sentence context. Young and older adults read sentences containing critical words with and without a HFN, where the HFN was congruent with prior sentence context, or not. This study produced several important findings: 1) Adult age differences in reading: older adults once again displayed evidence of a riskier reading strategy. (2) Effects of word misperception: this study demonstrated clear word misperception effects during normal sentence reading, such that readers sometimes misread a word as its HFN, particularly when the HFN was congruent with the prior sentence context. Further, Experiment 7 provides evidence for a visual component in HFN word misperception effects. (3) Adult age differences in word misperception: this study demonstrated that older adults may make more word misperception errors than young adults when reading a critical word with a HFN which is visually, as well as orthographically, similar to the critical word. Together, these two experiments presented here provide important insights into effects of word misperception and the use of sentence context in older age, which may be an important age difference in early word processing. Each of these key findings are discussed in turn.

Adult age differences in reading

In both Experiment 6 and Experiment 7 older adults displayed evidence of risky reading. Older adults skipped more words during first-pass reading than young adults, and also made more regressive saccades. This finding is in line with numerous previous studies investigating adult age differences in reading (e.g. Rayner, Reichle et al, 2006; see also Appendix A). However, one important difference between the results of Experiment 6 and Experiment 7 is that the older adults in Experiment 6 produced similar overall reading times to the young adults, whereas the older adults in Experiment 7 read more slowly than the young adults, suggesting that only the participants in Experiment 7 experienced greater reading difficulty. It may be that the participants in Experiment 6 were drawn from a more able older adult population who were able to utilise the risky reading strategy more effectively than the older adults in Experiment 7 (alternatively, it may be that the young adult group in Experiment 7 were less skilled readers than those in Experiment 6). This is an important demonstration of the role of individual differences in reading performance (see Chapter 6, Section 6.3.1). However, in both Experiments, the older adults outperformed the young participants on a standard vocabulary test. They also produced similar working memory performance on a digit span test and had normal visual acuity. Therefore, further work is needed to understand the factors determining individual performance.

Effects of word misperception

Both experiments show clear word misperception effects during natural reading, such that readers sometimes misread a word as its HFN, particularly when the HFN was congruent with the prior sentence context. In line with previous studies with young adults (Pollatsek et al., 1999; Slattery, 2009) the findings also showed that misreading a word as its HFN has a relatively late impact on eye movement behaviour and therefore may reflect efforts to repair this misanalysis by reprocessing the misread word. The mediating effect of context is also in line with previous research (Slattery, 2009). The current results expand on previous work to show that both young and older readers make use of sentence context to guide their reading and avoid a misperception when the HFN is not congruent with prior sentence context.

Notably, the results of Experiment 7 demonstrate the role of word shape in HFN effects. In line with the results of Marcet and Perea (2017; in press) these results suggest that word shape may play an important role in word identification. Currently models of visual word recognition (e.g. McClelland & Rumelhart, 1981; Coltheart et al., 2001, for a description of these models, see Chapter 1, Section 1.4.3) do not specify a role of word shape and so cannot fully account for these findings (see Chapter 6, Section 6.2.3 for a discussion). This is an important consideration for future model advancement. Further, these results suggest that a lexical competition account of word misperception may not be sufficient to fully explain HFN misperception effects as clearly visual, as well as lexical factors can play a role in driving this effect. To understand this in more detail, the extent to which visual similarity mediates word misperception in young adults still needs to be established (discussed further in Chapter 6, Section 6.2.3).

Adult age differences in word misperception

The current study found important evidence suggesting that older adults make more HFN word misperception errors than young adults, particularly when the HFN was congruent with prior sentence context. This finding supports the notion that older adults are more likely to guess the identities of words based on partial word information and sentence context. These findings build on previous studies such as Robert and Mathey (2007) suggesting that young and older adults respond differently to HFNs in isolated word recognition tasks. Crucially however, these previous experiments cannot address the issue of word misperception (indeed, in a LDT task as in Robert & Mathey, misperception of the presented word as its HFN would still results in a correct “yes” response, as they are both real words). Crucially, older adults only made more word misperception errors in Experiment 7 when HFNs were visually, as well as orthographically, similar to the critical word. This finding is in line with previous research suggesting that older adults may rely on coarse-scale cues such as the length and shape of words (e.g., Jordan et al., 2014) and sentence context (e.g Choi et al., 2017) than young adults to inform their guesses regarding word identify. Further, these results suggest that aspects of visual processing may differ in older age such that older adults find visually and orthographically similar words more confusable than young adults. In the context of models of eye movement control during reading, this may be reflected in future simulations by adjustments to the V parameter (visual processing), such that there may be greater confusability in high spatial frequency content between visually similar letters in this processing stage, particularly for older readers (see Chapter 6, Section 6.2.2). In order to understand the nature of this misperception in greater detail, it will be important to establish whether these misperceptions are often occurring in parafoveal vision (e.g. using a gaze-contingent manipulation), where age-related visual declines are particularly pronounced (Crassini et al., 1988, see also Chapter 6, Section 6.2.4).

Crucially, while these results do not rule out age differences in lexical competition, what these results do suggest is the importance of misperception based on visual similarity. Therefore, these findings have important implications for both models of visual word recognition and models of eye movement control during reading. Overall, these results suggest that older adults are more likely to misperceive certain types of words than young adults and this word misperception may be driven in part by the visual characteristics of a word.

5.5 Conclusion

In conclusion the present study provides novel insight into word misperception across the lifespan. These results show clear word misperception effects in natural reading, and further, demonstrate an important visual component to HFN word misperception effects. The role of visual similarity in HFN word misperception effects should be explored further in young adult readers. Overall, the results are in line with the risky reading hypothesis and provide important evidence that older adults may make more word misperception errors than young adults during normal sentence reading and make greater use of sentence context to inform their guesses regarding word identity. Crucially, however, this only seems to be the case when the critical word and the HFN are visually, as well as orthographically, similar. Word misperception may therefore be an important source of adult age differences in reading.

Chapter 6:

General Discussion

This thesis set out to examine whether young and older adult readers differ in aspects of early word recognition during reading and explore whether the mechanisms underlying these processes differ between young and older adult readers. The experiments presented in this thesis have provided novel insight into various aspects of early word recognition processes for older adults. Specifically, the topics examined in this thesis are: parafoveal processing and the perceptual span (Chapter 2); the impact of reduced stimulus quality on reading (Chapter 3); letter position coding processes (Chapter 4); and word misperception (Chapter 5). Chapter 6 reviews the findings and discusses the implications for understanding adult age differences in reading. Section 6.1 summarises the key novel empirical findings of the experiments presented in this thesis. Section 6.2 discusses the implications for understanding of adult age differences in various aspects of older adults' early word recognition processes during reading, with reference to both models of eye movement control during reading and models of visual word recognition. Section 6.3 discusses future directions that research in this area could take, including both specific follow-up studies to this thesis and more general issues for further research. Finally, Section 6.4 presents some overall conclusions.

6.1 Summary of key empirical findings

This thesis provides novel insights into early word recognition processes in older adults. Several of the issues in this thesis, such as effects of reduced text contrast, letter position coding processes and word misperception have not previously been explored for older adults using eye-tracking methodology. Further, previous research addressing issues relating to the perceptual span and use of sentence context by older adults have failed to provide a clear picture. This thesis has furthered understanding of both impaired and intact processing for healthy older adults. Table 6.1 shows how the current experiments fit within the literature exploring adult age differences in eye movements during reading and how these experiments contribute new understanding (i.e. three new categories have been added to the table).

The experimental work in this thesis began (Experiment 1) by exploring the processing of words outside of central fixation (in the parafovea) and employed a moving-window manipulation (see Chapter 1, Section 1.5.1) to explore the size of the perceptual span in young and older adults. Previous research produced mixed findings regarding whether the perceptual span changes in size and symmetry with advancing age (e.g. Rayner, Castelano & Yang, 2009; Whitford & Titone, 2016), and so Experiment 1 aimed to address this issue using an improved methodology (replacing letters outside of the window with visually similar letters, rather than the typical “x” mask used in moving-window studies). The findings indicated that parafoveal processing is not impaired in older age, with young and older adults displaying a perceptual span of similar size and symmetry. However, young and older adults’ behavioural responses to the removal of this information did differ, suggesting that there may be subtle differences in the way that this modulates reading processes within the span. Overall, Experiment 1 addresses the mixed findings regarding the extent of parafoveal processing in older age and indicates that reductions in the perceptual span may not be a key factor in age-related reading difficulty (see Chapter 2, Table 2.1).

Manipulation/variable examined	**Relevant studies**
Control of binocular fixations	Paterson, McGowan & Jordan (2013c)
Parafoveal processing/ the perceptual span	Rayner, Castelhano, & Yang (2009); Rayner, Castelhano, & Yang (2010); Rayner, Yang, Schuett, & Slattery (2014); Risse & Kliegl (2011); Whitford & Titone (2016); **Experiment 1**
Text spacing	McGowan, White, & Paterson (2015); McGowan, White, Jordan, & Paterson (2014); Rayner, Yang, Schuett, & Slattery (2013)
Word length	Kliegl, Grabner, Rolfs & Engbert (2004)
Spatial frequency filtering	Jordan, McGowan, & Paterson (2014); Paterson, McGowan & Jordan (2013a); Paterson, McGowan & Jordan (2013b)
Text contrast	**Experiments 2 & 3- Warrington, McGowan, Paterson & White (in press)**
Time course of visual processing	Liu, Pan, Tong, & Liu (2017); Rayner, Yang, Castelhano, & Liversedge (2011)
Visual complexity	Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)
Font difficulty	Rayner, Reichle, Stroud, Williams, & Pollatsek (2006)
Letter position coding	**Experiments 4 & 5- Warrington, McGowan, Paterson & White (submitted)**
Word frequency	Kliegl, Grabner, Rolfs & Engbert (2004); Rayner, Reichle, Stroud, Williams, & Pollatsek (2006); **Experiments 2 & 3- Warrington, McGowan, Paterson & White (in press);** Whitford & Titone (2017); Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)
Word misperception	**Experiment 6 -Warrington, White & Paterson (2018), Experiment 7**
Word predictability/ sentence context	Choi, Lowder, Ferreira, Swaab, & Henderson (2017); Kliegl, Grabner, Rolfs & Engbert (2004); Rayner, Reichle, Stroud, Williams, & Pollatsek (2006); Whitford & Titone (2017); **Experiment 6 -Warrington, White & Paterson (2018), Experiment 7**
Reading with distraction	Kember & McDowd (2006); Kemper, McDowd, Metcalf, & Liu (2008)
Syntactic complexity/ambiguity	Kemper, Crow, & Kemtes (2004); Kemper & Liu (2007); Stine-Morrow, Shake, Miles, Lee, Gao, & McConkie (2010)
Lexical complexity/ambiguity	Shake & Stine-Morrow (2011); Stites, Federmeier, & Stine-Morrow (2013)
Wrap-up effects	Payne & Stine-Morrow (2012)
Chinese reading	Liu, Pan, Tong, & Liu (2017); Wang, Li, Li, Xie, Chang, Paterson, White, & McGowan (in press); Zang, Zhang, Bai, Yan, Paterson, & Liversedge (2016)

Table 6.1. A reproduction of Table 1.1. also including experiments from the current thesis.

Experiments 2 and 3 manipulated the visual features of the text by reducing contrast for all words within a sentence (Experiment 2) or for just upcoming words (Experiment 3). These two experiments are novel in a number of ways. These are the first experiments to provide an assessment of the effects of reduced text contrast on older adults' eye movement behaviour. This is also one of the first experiments to examine the reading performance of middle-aged readers. Additionally, the study provides further insight into the role of stimulus quality on lexical processing, as research examining this issue for young adults is mixed (Jainta, Nikolova, & Liversedge, 2017; Liu, Li & Han, 2015; Sheridan & Reingold, 2013). Further, no studies have examined this issue for middle-aged or older readers. The results revealed that older adults experience greater difficulty in reading low-contrast text than young and middle-aged adults, and this increased difficulty is experienced both for text presented entirely at low-contrast, and when only parafoveal text is presented at low-contrast. However, this additional difficulty primarily affects older adults' visual, rather than lexical, processing of text[13]. In addition, the results of Experiment 2 provide an important initial indication that in middle-aged readers, reading is very similar to that of young readers and this group are not yet showing signs of greater reading difficulty. Overall the results indicate that low text contrast may be an important source of reading difficulty for older adults.

Experiments 4 and 5 examined letter position coding processes in young and older adults using words containing transposed letters at the beginning (*rpoblem*), internally (*porblem*), or at the end of a word (*problme*). In Experiment 4, the transpositions were present throughout reading, in Experiment 5 a gaze-contingent paradigm was employed such that when the eyes moved past a word with transposed letters it was then presented correctly. These experiments are the first to provide an examination of letter position coding during natural reading for older adults. The results suggest that young and older adults process letter position similarly. For both young and older adults, the position of the beginning letter is particularly important (in line with

[13] Stimulus quality and word frequency (an index of lexical processing difficulty) did interact in Experiment 2, suggesting that reducing the contrast of all words within a sentence does make word identification more difficult. As this chapter focuses on findings relating to adult age differences in reading, this is not discussed further here. A discussion of the implications of this finding can be found in Chapter 3, Section 3.4.

research for young adult readers e.g. White, Johnson, Liversedge, & Rayner, 2008), although disruption to eye movement behaviour occurs when any change is made to letter order, including internal letters. Therefore, older adults' reading difficulty does not appear to originate from differential difficulty in letter position processing either for word internal or external letters. These two experiments also highlighted the potentially important role of inflated effects due to repeated sampling (the "double-whammy" effect) when examining natural reading in older adults (discussed further in Section 6.2.4).

Finally, Experiments 6 and 7 examined whether older adults make more word misperception errors during reading than young adults, and additionally, whether this effect is modulated by sentence context. In these experiments, young and older adults read sentences containing critical words with and without a higher frequency neighbour (HFN), where the HFN was congruent with prior sentence context or not. In Experiment 6, HFNs could be visually similar or dissimilar to the critical word. In Experiment 7 all HFNs were visually similar to the critical word. These experiments are the first to address the issue of whether older adults make more word misperception errors during reading than young adults. Clear evidence of word misperception was found for both age-groups when the HFN was congruent with prior context, in line with previous research with young adults (e.g. Slattery, 2009). However, age differences in this effect were found only in Experiment 7, when critical words and HFNs were visually, as well as orthographically, similar. This suggests that older adults may be making particular use of visual cues, such as overall word shape, when guessing the identity of a word. These findings are also in line with the notion that older adults are "riskier" readers (Rayner, Reichle et al., 2006; see Section 6.2.4).

The results of these seven studies reveal important underlying mechanisms that begin to account for how age-related reading difficulties might arise. Experiments 2, 3, 6 and 7 all indicate a particularly important role of visual processing for older adults, and that increased visual processing difficulty (Experiments 2 and 3) or increased visual confusability (Experiment 7) can be particularly problematic for older adults. Importantly, these results also highlight areas where processing remains intact in older age. Notably, the perceptual span of older adults appears similar to that of young adults (Experiment 1) and letter position coding processes remain intact in older age

(Experiments 4 and 5). These results have important implications for understanding adult age differences in early word recognition processes during natural reading.

6.2 Key implications for understanding the mechanisms of early word recognition processes

This section considers how the experiments in the current thesis have informed understanding of the mechanisms underlying early word recognition processes in older adults. Several key issues are discussed in turn. Section 6.2.1 considers implications for understanding older adults' parafoveal processing of text. Section 6.2.2 considers implications for understanding older adults' visual processing of text. Each of these sections includes a consideration of how these findings fit within current models of eye movement control during reading. Section 6.2.3 considers the findings relating to letter position coding and lexical processing in the context of models of word recognition and letter encoding. Section 6.2.4 considers implications for the "risky" reading hypothesis in relation to early word recognition processes. Finally, Section 6.2.5 summarises Section 6.2.

6.2.1 Parafoveal processing of text

This section summarises how the experiments in this thesis have informed understanding of parafoveal processing in older age. As processing often begins before a word is fixated, parafoveal processing can be considered an important component of early word processing (see Chapter 1, Section 1.5.1 and Chapter 2, Section 2.1). Given the many visual difficulties that occur in parafoveal vision in older age e.g. effects of visual crowding (Scialfa, Cordazzo, Bubric, & Lyon, 2013; outlined in Chapter 1, Section 1.2) it is perhaps surprising that Experiment 1 indicated that young and older adults process parafoveal orthographic information from a similar region around fixation. This finding suggests that a reduction in parafoveal processing may not be a key component of adult age differences in reading (see Chapter 2, Table 2.1 for a comparison with previous studies). Previous research with older adults (Grabbe & Allen, 2013; Risse & Kliegl, 2011) has suggested that this span size can be attributed to the distribution of attention, rather than visual acuity (see also, Chapter 1, Section 1.5.1). Older adults may deploy attention in such a way that parafoveal processing is prioritised as part of a compensatory strategy to maintain reading speed (see also, Paterson, McGowan & Jordan, 2013a). However, Experiment 1 also demonstrated that older adults spent a greater time rereading when parafoveal information is not available, this may reflect older adults being less able to respond and adapt to changes in information availability (see Risse & Kliegl, 2011). However, in contrast to the evidence for intact parafoveal processing found in Experiment 1, the results of Experiment 3 (Chapter 3) suggest that older adults' parafoveal processing is disrupted more by reductions in stimulus quality than young adults. This indicates that age differences in parafoveal processing may exist under certain circumstances, such as when parafoveal information is more difficult to process. It could be that while young and older adults make use of parafoveal information from a similar region around fixation, there may be differences in the depth of processing undertaken.

Importantly, these results suggest that currently, neither the simulations within the E-Z reader model (Rayner, Reichle et al., 2006) nor the simulations within the SWIFT model (Laubrock, Kliegl, & Engbert, 2006) are fully accounting for older adults parafoveal processing (see Chapter 1, Section 1.3.6 for a description of these simulations). SWIFT simulations produced a more asymmetric perceptual span for older adults than for young adults. In line with previous empirical work (e.g. Whitford & Titone, 2016) the findings from Experiment 1 further suggest that this is not an accurate characterisation of the perceptual span in older age. E-Z reader highlights an effect of reduced parafoveal acuity on parafoveal processing, this suggestion may well be compatible with the findings of Experiment 3, however greater specificity regarding the circumstances under which parafoveal processing disrupted for older adults is needed (e.g. when text contrast is low, but not when reading normal high-contrast text). Future simulations may aim to produce a perceptual span of similar size for both age groups, at least under normal reading conditions. Further, current models cannot account for the behavioural differences seen in Experiment 1 when parafoveal information was not available. Further examination of the possibility that this reflects an age-related drop in the ability to respond and adapt their reading according to the information available is warranted.

6.2.2 Visual processing of text

The results from several experiments in this thesis point to potential age differences in the initial visual processing of text, which is another important component of early word processing. In Experiments 2 and 3 the visual processing of older readers was affected more than young readers by a reduction in text contrast. This was the case when both foveal and parafoveal information was low-contrast (Experiment 2) and when only parafoveal information was low-contrast (Experiment 3). This indicates that high-contrast is particularly important for older adults to read efficiently. Previous research has suggested that older adults rely to a greater extent than young adults on coarse-scale information, such as overall word shape (Jordan, McGowan & Paterson, 2014; Paterson, McGowan & Jordan, 2013 a,b). It may be that older adults have greater difficulty utilising these cues when text contrast is low.

Further evidence that older adults may rely more than young adults on the basic visual features of words comes from Experiment 7, in which older adults were more likely than young adults to misperceive a word as its HFN when the two words were visually, as well as orthographically similar. However, when words are orthographically similar, but not necessarily visually similar (Experiment 6), young and older adults were equally likely to make a word misperception error. Both Chapter 3 and Chapter 5 explore manipulations that have a lexical effect. In Chapter 3, there was an interactive effect of stimulus quality and word frequency when all words in the sentence were presented at low-contrast. The word misperception effect (Chapter 5) occurs only for higher frequency neighbours, and not lower frequency neighbours, and is often attributed to lexical competition (see section 6.2.3). However, in both cases, the results suggest that visual factors within the text may influence older adults' reading behaviour independently of lexical processing.

These findings regarding older adults' visual processing of text have important implications for models of eye movement control during reading. While E-Z reader simulations have been able to successfully capture the general pattern of adult age differences in eye movement behaviour (Rayner, Reichle et al., 2006), the current results indicate that the current parameter adjustments may not be sufficient to account for differences in early visual processing between young and older adults. Rayner, Reichle et al.'s simulations included changes to parameter ε, which modulates the effect of visual acuity limitations on the rate of lexical processing. However, in the present research Experiment 2 suggests stimulus quality affects older adults' reading behaviour independently of lexical processing. It therefore could be that other mechanisms are also crucial in accounting for changes in the effects of stimulus quality across the lifespan, such as the duration of the V stage in E-Z reader (see Chapter 1, Section 1.3.5, Figure 1.4 and Chapter 3, Section 3.4). V relates to pre-attentive visual processing. In this stage, low spatial frequency information enables programming of saccades to words and high spatial frequency information enables letter features to be processed. Stimulus quality may modulate the rate of pre-attentive visual processing within the V stage (see White & Staub, 2012). Accordingly, the time required for completion of pre-attentive visual processing may be longer for low- compared to high-contrast text, and this may especially be the case for older readers. Future simulations should consider this possibility. Similarly, adjustments to the V parameter may also account for the findings of Experiment 7, such that there may be greater confusability in high spatial frequency content between visually similar letters in this processing stage, particularly for older readers (the findings of Experiment 7 are discussed with reference to models of visual word recognition in Section 6.2.3). These findings raise some important questions regarding the basic structure of models of eye movement control during reading which require further exploration. An important question concerns whether lexical processing is indeed impaired in older age, as assumed by Rayner, Reichle et al. (2006, see also, Section 6.3.2), or if the nature of this difficult would be best characterised as a cascading effect resulting from early visual processing difficulties. This would have important implications not only for understanding adult eye differences in eye movement behaviour, but for characterising the structure of processing for both young and older adults. Suggestions for further research which may examine this assumption are made in Section 6.3. Current models of eye movement control do not implement cascading effects, however, this idea is central to several models of visual word recognition. Therefore, this research again highlights the need for an integrated model of reading behaviour (see Reichle, 2015). Overall, the findings from this thesis have provided an important indication that differences in visual processing may be a key component of adult-related reading difficulty.

6.2.3 Letter position coding, lexical processing and models of visual word recognition and encoding

Currently, how the processes underlying word recognition may change with age is not well specified in models of visual word recognition such as the Interactive Activation model (McClelland & Rumelhart, 1981) and the Dual-route Cascaded model (Coltheart, Rastle, Perry, Langdon, & Zieglar, 2001). Nevertheless, findings from the current thesis do have some important implications for understanding word recognition in both young and older adult readers. The implications for the coding of letter position and letter identity and the implications for lexical processing are discussed.

Letter identity coding

These findings also have important implications for understanding how letters are identified and in particular, how letters and words which are visually similar are identified. For simplicity, current models of visual word recognition (e.g. McClelland & Rumelhart, 1981; Coltheart et al., 2001) assume a minimal/null role of visual similarity across letters in lexical access and that lexical access takes place on the basis of abstract letter representations that are attained early in processing (Grainger, Dufau, & Ziegler, 2016). Therefore, these models would predict that words primed by a word containing a visually similar letter substitution (nevtral–NEUTRAL) would be processed at the same speed as a word primed by a visually dissimilar letter substitution (neztral–NEUTRAL). However, this does not appear to be the case (Marcet & Perea, 2017; in press). Chapter 5 (Experiments 6 & 7) not only produced HFN word misperception effects, but also found that older adults were particularly likely to misperceive a word as its HFN when the two words were visually, as well as orthographically, similar. This suggests that there is some degree of ambiguity concerning letter identities, particularly in early word processing (when these misperceptions are taking place). Indeed, much research has suggested that the processes underlying word recognition can be better understood assuming a noisy or incomplete visual input in early processing (Adelman, 2011; Davis, 2010; Grainger et al., 2016; Norris, Kinoshita, & van Casteren, 2010). Future developments of models need to consider how letter representations are encoded from their visual features and explore how visual information is mapped onto abstract representations (see Grainger et al., 2016).

Letter position coding

The findings from Experiments 4 and 5 further support the argument that the strict letter position coding system employed by the Interactive Activation model (McClelland & Rumelhart, 1981) and the Dual-route Cascaded model (Coltheart et al., 2001) in which letter identity and letter position are coded at the same time is implausible. The finding of Experiments 4 and 5 are in line with the predictions of models that employ flexible letter position coding (e.g. SERIOL, Whitney, 2001; SOLAR, Davis & Bowers, 1996; The Overlap Model, Gomez, Ratcliff & Perea, 2008) (see Chapter 4, Section 4.1). However, these models are not able to fully account for effects of letter position and the privileged role of the first letter. The continuous open bigram coding scheme employed in the SERIOL model (Whitney, 2001) specifies that lateral inhibition from adjacent letters can reduce activation. Thus, this model would predict that transpositions of external letters are more disruptive than transpositions of internal letters. This is also compatible Johnson and Eisler's (2012) findings for end letters, suggesting that they are important due to reduced lateral interference (but does not capture their findings for beginning letters). However, the spatial coding employed in the SOLAR model (Davis, 1999; Davis, & Bowers, 2006) predicts that internal letters are more important than word end letters. Therefore, these models may be limited in what they can tell us about letter position coding and may be best considered in combination with lexical explanations such as the argument that the initial letter is especially important for constraining the number of lexical candidates (Broerse & Zwaan, 1966; Clark & O'Regan, 1999; Hand, O'Donnell & Sereno, 2012; Lima & Inhoff, 1985; White et al., 2008). For a further consideration of the role of letter position, see Chapter 4, Section 4.1.

Lexical processing

A key assumption of several successful models of visual word recognition is that processing is interactive (Coltheart et al., 2001; McClelland & Rumelhart, 1981) see Chapter 1, Section 1.4.3 for a description of these models). Therefore, these models would predict that the word frequency effect should be larger for visually degraded input since the slower uptake of featural letter information should have more of an influence for low frequency words, as they are further from the recognition threshold (Balota, Aschenbrenner, & Yap, 2013). In line with this, Experiment 2 found an interactive effect of stimulus quality and word frequency. This provides an important indication that the basic interactive structure of these models is accurately reflecting processing for both young and older adults (see Chapter 3, Section 3.4). This Experiment also provided some evidence that under normal reading conditions, the word frequency effect is larger for older adults such that they recognise low frequency words particularly slowly, in line with several previous studies (Kliegl et al., 2004; McGowan, White & Paterson, 2015; Rayner, Reichle et al., 2006; Whitford & Titone, 2017; see Chapter 1, Section 1.4.5). This may be accounted for by a slower rate of lexical processing (as processed in E-Z reader simulations, Rayner, Reichle et al., 2006) (but may also in part reflect a "double-whammy", see Section 6.3.2).

The results from Experiments 6 and 7 may have important implications for the assumption that neighbour misperception effects occur as a result of lexical competition from a word's orthographic neighbours (see Chapter 1, Section 1.4.3). Experiment 7 demonstrated that older adults only make more HFN word misperception errors when a critical word and its HFN are visually, as well as orthographically, similar. Indeed, research has suggested that a word's orthographic neighbours are not strongly activated during parafoveal processing (Williams, Perea, Pollatsek, & Rayner, 2006).

While it remains to be determined whether misperceptions often occur in parafoveal vision (a gaze-contingent manipulation would be needed to explore this, see Section 6.2.4), in Experiment 7, when the sentence context was neutral, words with a HFN were more likely to be skipped than words without a HFN (for older adults, these words were skipped on around 25% of the time). Therefore, if the decision regarding a word's identity is often made in parafoveal vision, lexical completion may not necessarily be the key factor driving this effect particularly in cases where that decision regarding a word's identity is made in parafoveal vision. Even if lexical competition is occurring, clearly this is not the only factor, and visual processing must also play a role. Further research is needed to explore the nature of this effect both in young and older adults (see Section 6.3.1 for future research suggestions). These results again suggest that more work is needed to understand the nature of lexical processing difficulties in older age and to consider whether these differences may be best characterised as a downstream effect resulting from visual processing difficulty.

6.2.4 The "risky" reading hypothesis

The experiments in this thesis have tested the "risky" reading hypothesis in a variety of ways and considered how early word processing may be important in driving risky reading behaviour. This section summarises the basic characteristics of older adults' eye movement behaviour, considers whether the reading task may play a role in risky reading and also discusses a key test of risky reading.

The characteristics of older adults' eye movement behaviour

Whether older adults are more risky readers has been a topic of some debate in recent eye movement articles. Since its introduction by Rayner, Reichle et al. in 2006, this hypothesis has been the most prominent account of adult age differences in reading. Previous simulations (McGowan & Reichle, 2018; Rayner, Reichle et al., 2006) have indicated that a risky reading strategy is sufficient to account for older adults' eye movement behaviour during reading. The experiments presented throughout this thesis provide clear support for the notion that older adults are riskier readers than young adults. Experiments 1, 2, 3 ,4 ,5 and 7 all found longer overall reading times for older adults compared to young adults. In addition, in all experiments older adults made more regressive saccades than young adults (although in Experiment 6 this was only significant for the critical word analyses). Older adults skipped words more often than young adults in Experiments 1, 4, 6 and 7. Further numerical trends towards greater word skipping for older adults were also found in Experiments 3 and 5 (for a summary, see Appendix A, Table A-1). Further, this thesis has helped to reveal the time-course of the development of these age effects, with Experiment 3 providing an initial indication adult age differences are not yet apparent in middle-aged readers. These findings are particularly important because several recent studies have failed to find such skipping differences (Whitford & Titone, 2016, 2017) and some have argued that there is no substantial evidence that older adults are riskier readers (Choi, Lowder, Ferreira, Swaab, & Henderson, 2017).

Factors that may modulate "risky" reading behaviour

The findings of Chapter 3 indicate that older adults may not always adopt a risky reading strategy. In Experiments 2 and 3, older adults appeared to adopt a more careful reading strategy, particularly in Experiment 2, such that when all words in a sentence were low-contrast, skipping rates were equal for young and older adults. Previous research has suggested that when a reading task is made more difficult e.g. by having more/ harder comprehension questions, older adults adopt a more careful reading strategy (Wotschack & Kleigl, 2013). In Chapter 3 the text contrast manipulation may be acting in a similar way by making the reading task more difficult (e.g. making it harder to determine word boundaries and so harder to plan skips). This may go some way to explaining the discrepant results across different studies. Both Whitford and Titone (2016; 2017) and Choi et al. (2017) employed comprehension questions after every sentence and so may have promoted a more careful reading strategy, akin to that seen in Wotschack and Kleigl (2013). These results may therefore have important implications for understanding the nature of risky reading. These results may also have important implications for models of eye movement control during reading. Different task demands may modulate readers' "standards of coherence" (van den Broek, Lorch, Linderholm & Gustafson, 2001; van den Broek, Risden & Husebye-Hartmann, 1995) and this may differentially affect reading behaviour across adult age. Future model developments should seek to reflect the role of task demands and the reader's goals in driving behaviour.

This thesis also highlights important individual differences in the effectiveness with which older adults are able to utilise this risky strategy. In Experiment 6 older adults produced similar overall reading times to the young adults despite skipping words more frequently. Individual reading ability may therefore play an important role in risky reading (see Section 6.3.1).

Does "risky" reading lead to greater word misperception?

While the risky reading hypothesis has been longstanding and incredibly influential, several of the key predictions of this hypothesis have not previously been examined directly. While a variety of studies note this increased skipping behaviour, the notion that this results from increased guessing of word identities based on partial word information, as Rayner, Reichle et al. (2006) hypothesise, has not been explored previously. Therefore, central to understanding if the adoption of a risky reading strategy can account for the characteristic pattern of eye movements in older readers is to determine whether older adults do indeed guess the identities of upcoming words. If this is the case, then we would expect them to make more word misperception errors and to make greater use of context to guide their guesses. Experiment 7 provides support for this notion by demonstrating that older adults are more likely than young adults to mistake a critical word for its visually similar HFN when the HFN was congruent with prior sentence context. These findings also begin to shed some light on the factors determining when older adults will make more errors and highlights the importance of word shape (see Sections 6.2.2 & 6.2.3). Overall, these findings indicate that differences in word processing, such as visual processing may play a role in risky reading and may contribute to word misperception.

Further tests of word misperception

There is much scope to further explore the nature of word misperception effects, both in young and older adults. In particular, a further study employing previews of HFNs could explore whether word misperception is particularly likely to occur in the parafovea (see Section 6.2.3 and Williams et al., 2006). In addition, to explore the role of lexical competition in word misperception, the response to visually similar HFN and visually dissimilar HFNs in young adults could be compared. This would help to disentangle the influence of visual and lexical processing in driving these effects. These issues are theoretically important and test the structure of current models of word recognition.

Further research may wish to explore the broader implications of word misperception for older adults' reading, including higher-level processing. An important question concerns whether word misperception may sometimes go unnoticed, or not be properly corrected, resulting in incomplete or inaccurate understanding. This could be investigated by, for example, examining eye movements in response to stimuli containing anomalous or ambiguous information such as garden-path sentences ("The horse raced past the barn fell."; Bever, 1970) or syntactically ambiguous sentences ("When Sue tripped the girl fell over and the vase was broken";

Wonnacott, Joseph, Adelman, & Nation, 2016). Comprehension questions could also probe understanding of these sentences and detect if they have been interpreted correctly.

In addition, further work is needed to understand the extent to these differences in eye movement behaviour and word misperception reflect the use of different reading strategies by young and older adults. Indeed, experiments such as those proposed above may play an important role in revealing this. An important test of this hypothesis may be to examine young and older adults reading behaviour when explicit instructions manipulate the reader's "standards of coherence" (van den Broek et al., 2001; van den Broek et al., 1995) by instructing them to read particularly carefully or to skim read. This would also provide an important test of the suggestion by Risse and Kliegl (2011) that older adults are less able to flexibly respond to task demands and would help to uncover the precise nature of risky reading behaviour.

6.2.5 Summary & Importance

These findings make a clear contribution to understanding of adult age differences in reading and have helped to reveal important underlying mechanisms that begin to account for how age-related reading difficulties might arise. Several experiments in this thesis have examined previously unexplored issues and produced novel findings highlighting the importance of differences in early word processing in adult age differences in reading.

These findings have important theoretical implications and have provided unique insight into how individual words are recognised within natural sentence reading, both in foveal and parafoveal vision. A key aim of future research must be to move towards an integrated model of reading, incorporating word recognition and eye movement control (see Reichle, 2015). These experiments have also highlighted several issues that a comprehensive model would need to address. Firstly, several experiments in this thesis point to age differences in visual processing. This is particularly important as this highlights that even older adults with normal visual acuity (as in the current experiments) suffer visual processing difficulties. Moving forward, it will be important to understand the precise contribution of visual and cognitive declines to different aspects of processing and further, to understand how these deficits may interact.

Further, as noted in Experiment 2, this early visual processing difficulty also affects lexical processing. Importantly, this suggests that future research should consider that lexical processing difficulties in older adults may stem from early differences in visual processing (this may also have important implications for studying groups with more severe deficits e.g. dementia, see Section 6.3.1).

Experiment 2 also highlighted that older adults may have an impaired ability to flexibly adapt their patterns of fixation in response to task demands (Risse & Kliegl, 2011) and this may reflect poorer executive control. Further the role of task demands, and readers' goals may differentially affect young reading behaviour across the adult lifespan (van den Broek et al., 1995; 2001). These factors, and many others, would need to be considered in a comprehensive account of adult age differences in reading.

6.3 Future research directions

Section 6.3 considers future research directions. Section 6.3.1 discusses some key issues and Section 6.3.2 considers the methodological considerations for future research.

6.3.1 Key issues for future research

This thesis has shed light on several important issues. However, there is still much scope for further research. Just a few suggestions are summarised here. In this section, suggestions for future studies and future research methods are considered.

Individual differences

As reading performance varies considerably across experiments and across different groups of older adults (e.g. Experiment 2 and Experiment 6) an in-depth examination of visual function, memory and vocabulary may help to provide better understanding about which factors may be protective against age-related declines in reading performance. Indeed, in the current experiments, older adults' visual acuity is always good, but more comprehensive tests incorporating parafoveal acuity, visual crowding etc. may provide greater insight. In Experiments 6 and 7 individual digit span and vocabulary performance was not predictive of word misperception. However, a more fine-grained analyses of these factors will be important in future studies, perhaps incorporating more complex language and memory tasks which may uncover more subtle deficits not captured by the tests employed in Experiments 6 and 7. Further, visual and cognitive factors are likely to have differential importance depending on the reading task and nature of the stimuli (e.g. working memory may be particularly important when reading syntactically complex sentences, see Chapter 1, Section 1.2.2). Exploring these issues will have important theoretical implications for models of eye movement control during reading.

Universality

Most research to date has examined adult age differences in the reading of Latinate languages (e.g. English, German). It will be important for future research to consider the extent to which processing is universal. A recent investigation of young readers of English, Finnish and Chinese demonstrated that there is great universality in the reading behaviour of young adult readers of different languages (Liversedge, Drieghe, Li, Yan, Bai, & Hyönä, 2016). However, recent experiments examining the reading of older Chinese readers has indicated that the precise manifestation of adult age differences in reading may not be universal. Notably, rather than adopting a risky reading strategy, older Chinese readers read particularly carefully and skip words infrequently (Wang et al., in press). As written Chinese is far more visually complex than written English it would also be interesting to explore whether the reading of older Chinese readers mimics the reading of older English readers completing a more difficult reading task.

There is also some suggestion that the nature of adult age differences in early word recognition may differ across languages (e.g. Liu et al., 2015 found additive effects of stimulus quality and word frequency in Chinese, see Chapter 3 for a discussion of these findings). Therefore, manipulations similar to those employed in this thesis may be very useful in uncovering these differences. Exploring languages of various orthographies and compositions (e.g. Arabic, Thai) will further inform our overall understanding of the reading process, not just for young adults, but for readers of all ages and will be crucial for forming a fully comprehensive theoretical understanding of reading processes across the adult lifespan.

More severe reading impairments

As we gain a fuller understanding of the effects of normal ageing on reading it will become important to understand reading in those with more severe reading impairments, both visual and cognitive (a summary of visual and cognitive changes in normal ageing can be found in Chapter 1, Section 1.2). A variety of age-related visual impairments are already well documented and, in some cases, reading aids are being developed (Walker, Bryan, Harvey, Riazi, & Anderson, 2016). Further, it has been demonstrated that older adults with MCI/dementia show slower reading and lower text comprehension than healthy older adults (Fernandez et al., 2013; 2014; 2015). The Experiments in this thesis have demonstrated the important role of early visual processing in driving adult age differences in reading for healthy older adults. Previous research has also pointed to an important role of poor vision in understanding decreased cognitive performance (Chen, Bhattacharya, &Pershing, 2017; Rogers & Langa, 2010). Therefore, visual declines may be an important mediating factor in reading performance in both normal and abnormal ageing. Understanding how and why these individuals processing differs from the processing of healthy older adults will both aid in the development of effective inventions and improve theoretical understanding of the reading process. Specifically, research could explore whether differences in early word recognition processes may characterise these impairments.

6.3.2 Methodological future directions

The “double-whammy” effect

This thesis has highlighted an important methodological consideration for future research. Researchers should be aware that the characteristic pattern of eye movements produced by older adults can contribute to older adults experiencing a “double-whammy” effect of experiencing difficult to read words both on first-pass and in subsequent rereading (described in Chapter 4). When comparing groups of readers with differential rates of regressions, word characteristics that modulate first-pass reading may also inflate overall reading times simply because those words are more likely to be sampled again during rereading. This highlights the importance of analysing and reporting eye movement measures across the eye movement record to fully capture and understand the performance of older adult readers. Importantly, some manipulations of word characteristics may incur both lexical and post-lexical processing difficulty. In such cases it may be difficult to differentiate the "double-whammy" effect of repeated lexical processing difficulty, from additional difficulty associated with post-lexical integration (e.g. word frequency manipulations may be associated with difficulties in lexical access and identification, but also difficulties integrating low-frequency words into sentential context). For further discussion, see Chapter 4, Section 4.4). This is an important consideration for models of eye movement control during reading and the possibility of such effects should be considered to avoid misinterpretation of effects. This may also contribute to the age x word frequency interaction in Experiment 2.

Reading across the lifespan

It is important to establish when in the lifespan age-related reading difficulty typically becomes apparent. While Experiment 2 provided an important initial indication that adult age differences in reading performance are not yet present in middle-aged adults (in this case, those aged 40-51), further research is needed in order to examine the precise trajectory of these changes across the lifespan. A large-scale study with participants of a variety of ages reading normally presented sentence may be particularly informative. Such experiments may also help to identify the appropriate age at which to implement any reading interventions.

Innovative methods- co-reregistration

While eye movements are widely regarded as the optimal method to study reading and can be used to infer the underlying cognitive processes, they do not provide a direct measure of neural activity. Many research findings have also come from EEG studies examining event-related potential (ERP) correlates of word recognition. However, a major limitation of these studies is that typically sentences are presented word-by-word to avoid eye movement artefacts. Further, findings from ERP studies have sometimes been difficult to reconcile with the findings of eye movement studies e.g. effects of word predictability in older age (Wlotko, Federmeier, & Kutas, 2012).

Recently, methods have been developed that enable the co-registration of eye-movements and ERPs. This approach records ERPs that occur during specific fixations on words (called fixation-related potentials or FRPs) and provides snapshots of activity in the brain as this occurs in real-time during natural reading. This method has proven to be effective in young adults (Kretzschmar, Schlesewsky & Staub, 2015). Crucially, to date, no studies have employed this method with older adults.

6.4 Conclusions

This thesis reports seven experiments which examined whether young and older adult readers differ in aspects of early word recognition during. Findings from Experiment 1 indicate that young and older adults make similar use of parafoveal orthographic information have a perceptual span which is similar in size and symmetry. Experiments 2 and 3 revealed that older adults experience greater difficulty in reading low-contrast text than young adults, and this increased difficulty is experienced both for text presented entirely at low-contrast, and also when parafoveal text is presented at low-contrast. Further, Experiment 2 provided an initial indication that the reading of middle-aged readers is similar to young adults and those (aged 40-51) do not yet experience the reading difficulty typically associated with older age. Experiments 4 and 5 suggest that young and older adults process letter position similarly and reading words with transposed letters does not appear to cause particular difficulties for older adults. The results of these two experiments also highlighted the important possibility of the role of ‘double-whammy’ effects when examining natural reading in older adults. Finally, Experiments 6 and 7 found evidence that older adults may make more word misperception errors during reading as they misperceived as visually similar HFN as the critical word more often than young adults when the HFN fit with prior sentence context. These findings are in line with the notion that older adults are riskier readers. Overall, these experiments have advanced our understanding of adult age differences in early word recognition processes have highlighted key areas for development in future studies, models of eye movement control during reading and models of visual word recognition.

Appendices

Appendix A

Summary of adult age differences in reading for sentence-level measures in each Experiment. For Experiment 1-5 this includes only the normal text condition. For Experiment 6 & & this is collapsed across conditions (as text was presented normally in all conditions).

	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5	Ex 6	Ex7
Sentence reading time (ms)							
Numerical difference	335	538	456	698	217	-42	360
Significant?	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	No	**Yes**
Fixation duration (ms)							
Numerical difference	17	15	20	0	6	-3	1
Significant?	**Yes**	No	**Yes**	No	No	No	No
Number of first-pass skips							
Numerical difference	0.7	0.1	0.4	0.5	0.5	0.6	0.6
Significant?	**Yes**	No	No	**Yes**	**Yes**	**Yes**	**Yes**
Number of regressive saccades							
Numerical difference	0.7	0.6	0.9	1.8	0.4	0.1	0.9
Significant?	**Yes**	**Yes**	**Yes**	**Yes**	No	No	**Yes**

Table A-1. Numerical age effects for each experiment.

Appendix B

ANOVA statistics for Experiment 1, 2 x 2 x 2 analyses.

		Sentence Reading Time		Average Fixation Duration		Progressive Saccade Length		Number of Progressive Saccades		Number of Regressive Saccades	
		F1	***F2***	***F1***	***F2***	***F1***	***F2***	***F1***	***F2***	***F1***	***F2***
Direction: Left or Right	*F*	240.55*	24.55*	40.37*	37.51*	84.12*	361.99*	50.68*	79.54*	13.97*	17.60*
	η_p^2	.876	.187	.543	.260	.712	.772	.598	.428	.291	.141
Size: Zero or One	*F*	17.48*	222.45*	82.29*	72.89*	37.01*	88.64*	252.78*	300.30*	138.71*	108.54*
	η_p^2	.340	.675	.708	.405	.521	.453	.881	.737	.803	.504
Direction x Age	*F*	1.21	0.52	0.00	0.12	1.66	5.46*	1.43	2.19	0.03	0.06
	η_p^2	N/A	N/A	N/A	N/A	N/A	.049	N/A	N/A	N/A	N/A
Size x Age	*F*	0.35	2.57	9.15*	14.35*	0.24	0.49*	0.70	1.03	15.22*	19.78*
	η_p^2	N/A	N/A	.212	.118	N/A	N/A	N/A	N/A	.309	.156
Direction x Size x Age	*F*	0.64	1.30	0.69	0.85	2.34	2.62	0.80	1.40	0.63	1.26
	η_p^2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table A-2. ANOVA statistics for 2 X 2 X 2 analyses. * indicates significance at the $p < .05$ level. Continued on next page.

		First-pass Reading Time		Number of First-pass Skips		Rereading Time	
		***F*1**	***F*2**	***F*1**	***F*2**	***F*1**	***F*2**
Direction: Left or Right	*F*	158.12*	204.30*	207.94*	307.73*	0.08	0.10
	η_p^2	.823	.794	.859	.853	N/A	N/A
Size: Zero or One	*F*	205.86*	184.96*	160.46*	238.57*	90.41*	72.00*
	η_p^2	.858	.777	.825	.818	.727	.576
Direction x Age	*F*	1.32	4.82*	0.21	0.61	0.08	0.09
	η_p^2	N/A	.083	N/A	N/A	N/A	N/A
Size x Age	*F*	5.19*	7.35*	0.06	0.11	1.28	2.16
	η_p^2	.132	.112	N/A	N/A	N/A	N/A
Direction x Size x Age	*F*	0.23	0.69	0.09	0.23	1.50	2.07
	η_p^2	N/A	N/A	N/A	N/A	N/A	N/A

Table A-2 continued

Appendix C

Log transformed LMEM statistics. Note that as data for binomial variables cannot be log-transformed, these variables have been removed from the tables.

		Sentence Reading Time (ms)	Average Fixation Duration (ms)	Number of Fixations	Progressive Saccade Length (characters)	Number of Progressive Saccades	Number of Regressions	First-pass Reading Time (ms)	Rereading Time (ms)	Number of First-Pass Skips
Age										
Young vs. Older	***β***	0.80	1.20	2.06	0.12	0.91	0.89	0.75	522.81	0.09
	SE	0.40	0.80	0.90	0.20	0.56	0.39	0.42	177.39	0.45
	t	4.10*	3.31*	2.30*	1.00	1.62	2.30*	2.50*	2.95*	0.19
Middle vs. Older	***β***	0.65	0.92	1.78	0.11	0.85	0.73	0.80	680.77	0.15
	SE	0.40	0.80	0.90	0.20	0.56	0.39	0.42	178.00	0.45
	t	3.52*	2.86*	1.98*	0.57	1.53	1.94	2.10*	3.32*	0.33
Young vs. Middle	***β***	0.52	0.30	0.28	0.19	0.05	0.16	0.09	157.96	0.06
	SE	0.39	0.80	0.90	0.20	0.56	0.39	0.42	178.27	0.45
	t	0.59	0.44	0.32	0.97	0.10	0.41	0.42	0.89	0.13
Contrast										
High vs. Low	***β***	0.48	0.65	0.98	0.12	0.59	0.20	0.39	210.10	0.39
	SE	0.05	0.08	0.14	0.02	0.06	0.08	0.08	53.54	0.33
	t	7.90*	9.62*	7.24*	6.97*	9.18*	2.42*	10.12*	3.92*	12.02*
Interactions										
Young vs. Older x Contrast	***β***	1.10	0.95	1.88	0.05	0.86	0.70	0.91	531.32	0.41
	SE	0.15	0.30	0.33	0.05	0.56	0.20	0.28	127.53	0.08
	t	6.00*	5.63*	5.71*	0.90	5.52*	3.45*	6.13*	4.17*	5.18*
Middle vs. Older x Contrast	***β***	0.75	0.80	1.41	0.06	0.69	0.40	0.80	463.28	0.36
	SE	0.15	0.30	0.33	0.04	0.56	0.20	0.28	129.80	0.08
	t	5.06*	4.84*	4.27*	1.48	4.44*	1.98*	4.95*	3.60*	4.55*
Young vs. Middle x Contrast	***β***	0.20	0.15	0.47	0.03	0.16	0.30	0.24	68.03	0.05
	SE	0.15	0.30	0.33	0.04	0.55	0.20	0.28	129.92	0.08
	t	0.94	0.79	1.43	0.74	1.05	1.37	1.18	0.52	0.64

Experiment 2 log-transformed statistics for global analyses

		First-Fixation Duration (ms)	Gaze Duration (ms)	Total Reading Time (ms)
Age				
Young vs. Older	***β***	0.40	0.39	0.30
	SE	0.07	0.08	0.08
	t/z	3.80*	3.25*	3.80*
Middle vs. Older	***β***	0.32	0.35	0.29
	SE	0.07	0.08	0.08
	t/z	3.64*	3.40*	3.86*
Young vs. Middle	***β***	0.02	0.01	0.01
	SE	0.07	0.08	0.08
	t/z	0.17	0.27	0.06
Frequency				
High vs. Low Frequency	***β***	0.22	0.18	0.18
	SE	0.06	0.02	0.01
	t/z	10.34*	13.61*	15.24*
Contrast				
High vs. low	***β***	0.35	0.23	0.24
	SE	0.08	0.03	0.02
	t/z	11.99*	8.63*	11.05*
Age x Frequency				
Young vs. Older x Frequency	***β***	0.04	0.05	0.04
	SE	0.05	0.05	0.03
	t/z	0.95	1.00	2.14*
Middle vs. Older x Frequency	***β***	0.03	0.05	0.05
	SE	0.05	0.05	0.03
	t/z	0.98	1.65	1.70
Young vs. Middle x Frequency	***β***	0.03	0.01	0.01
	SE	0.05	0.05	0.03
	t/z	0.09	0.51	0.49
Age x Contrast				
Young vs. Older x Contrast	***β***	0.29	0.31	0.31
	SE	0.04	0.04	0.05
	t/z	7.10*	6.00*	7.22*
Middle vs. Older x Contrast	***β***	0.28	0.29	0.30
	SE	0.03	0.04	0.05
	t/z	5.63*	5.60*	5.84*
Young vs. Middle x Contrast	***β***	0.15	0.12	0.09
	SE	0.03	0.04	0.05
	t/z	0.73	0.63	1.60
Contrast x Frequency				
Contrast x Frequency	***β***	0.16	0.08	0.06
	SE	0.04	0.02	0.02
	t/z	2.64*	3.32*	2.73*
Age x Contrast x Frequency				
Young vs. Older x Contrast x Frequency	***β***	0.05	0.05	0.03
	SE	0.07	0.08	0.06
	t/z	0.70	0.70	0.40
Middle vs. Older x Contrast x Frequency	***β***	0.05	0.05	0.02
	SE	0.07	0.08	0.06
	t/z	0.56	0.76	0.35
Young vs. Middle x Contrast x Frequency	***β***	0.04	0.05	0.02
	SE	0.07	0.08	0.06
	t/z	0.62	0.91	0.36

Experiment 2- log-transformed statistics for local analyses.

		Sentence Reading Time (ms)	Average Fixation Duration (ms)	Number of Fixations	Progressive Saccade Length (characters)	Number of Progressive Saccades	Number of Regressions	First pass Reading Time (ms)	Rereading Time (ms)	Number of First Pass Skips
Age	***β***	0.26	0.11	0.01	0.14	0.02	0.25	0.2	99.66	0.2
	SE	0.08	0.03	0.06	0.05	0.06	0.11	0.06	38.30	0.2
	t	3.36*	3.17*	1.82	0.42	0.35	2.48*	2.28*	2.78*	0.49
Preview contrast	***β***	0.13	0.06	0.01	0.30	0.10	0.01	0.2	2.36	0.6
	SE	0.02	0.01	0.01	0.02	0.01	0.04	0.01	11.35	0.3
	t	8.79*	8.04*	5.90*	7.03*	8.28*	0.07	11.35*	0.10	8.42*
Age x Preview contrast	***β***	0.13	0.44	0.01	0.20	0.10	0.04	0.2	21.94	0.6
	SE	0.03	0.01	0.02	0.02	0.02	0.08	0.03	22.20	0.1
	t	4.50*	2.69*	4.10*	2.71*	4.46*	0.52	5.96*	1.13	4.74*

Experiment 3- log-transformed statistics for global analyses.

		First-fixation duration (ms)	Gaze Duration (ms)	Total Reading Time (ms)
Age	***β***	0.21	0.3	0.22
	SE	0.07	0.04	0.05
	t/z	4.22*	3.61*	3.94*
Frequency	***β***	0.06	0.2	0.10
	SE	0.03	0.08	0.03
	t/z	5.57*	6.97*	7.39*
Preview contrast	***β***	0.10	0.1	0.10
	SE	0.03	0.03	0.03
	t/z	4.03*	3.99*	3.62*
Age x Frequency	***β***	0.03	0.1	0.03
	SE	0.05	0.03	0.05
	t/z	1.37	1.16	0.48
Age x Preview contrast	***β***	0.06	0.1	0.01
	SE	0.07	0.05	0.05
	t/z	2.65*	1.07	2.50*
Preview contrast x Frequency	***β***	0.02	0.1	0.02
	SE	0.06	0.05	0.06
	t/z	0.95	1.48	0.65
Age x Preview contrast x Frequency	***β***	0.01	0.1	0.01
	SE	0.11	0.09	0.11
	t/z	0.13	1.33	0.31

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time (ms)	Number of first-pass skips	Rereading time (ms)
Intercept	***β***	8.04	251.54	2.48	0.98	7.62	1.18	6.64
	SE	0.04	3.69	0.04	0.07	0.04	0.06	0.07
	t	187.37*	68.28*	64.83*	14.09*	200.19*	20.16*	89.88*
Age								
Young vs. Older	***β***	0.29	0.76	0.22	0.61	0.04	0.14	0.75
	SE	0.08	7.20	0.07	0.14	0.07	0.10	0.14
	t	3.42*	0.11	3.00*	4.54*	0.54	1.35	5.30*
Text Type								
Normal vs. word-beginning	***β***	0.32	0.07	0.23	0.30	0.19	0.10	0.49
	SE	0.02	0.09	0.02	0.04	0.02	0.02	0.06
	t	14.66*	8.10*	12.14*	7.60*	10.02*	5.95*	7.98*
Normal vs. Internal	***β***	0.10	0.03	0.06	0.04	0.07	0.05	0.13
	SE	0.02	0.01	0.01	0.04	0.02	0.02	0.06
	t	6.00*	3.20*	4.57*	1.03	3.97*	2.84*	2.11*
Normal vs. word-end	***β***	0.22	0.04	0.20	0.14	0.17	0.12	0.28
	SE	0.02	0.01	0.02	0.04	0.02	0.02	0.06
	t	10.30*	5.00*	9.81*	3.89*	10.48*	5.11*	4.21*
Age x Text Type								
Age x Normal vs. word-beginning	***β***	0.06	0.01	0.08	0.04	0.00	0.01	0.01
	SE	0.03	0.02	0.03	0.06	0.04	0.04	0.11
	t	1.97*	0.60	2.58*	0.62	0.12	0.26	1.55
Age x Normal vs. Internal	***β***	0.05	0.00	0.07	0.05	0.04	0.03	0.05
	SE	0.03	0.02	0.02	0.06	0.03	0.03	0.06
	t	1.48	0.20	1.88	0.78	1.22	0.75	0.13
Age x Normal vs. word-end	***β***	0.06	0.01	0.04	0.03	0.04	0.05	0.10
	SE	0.04	0.01	0.03	0.07	0.03	0.04	0.13
	t	0.85	0.40	1.25	0.45	1.36	1.28	0.75

Experiment 4 log-transformed LMEM statistics.

		Sentence reading time (ms)	Fixation duration (ms)	Number of fixations	Number of regressive saccades	First-pass reading time	Number of first-pass skips	Rereading time
Intercept	***β***	7.94	5.45	2.37	0.78	7.64	1.45	6.22
	SE	0.06	0.02	0.05	0.07	0.05	0.04	0.09
	t	127.80*	220.80*	48.82*	10.59*	152.41*	34.59*	68.64*
Age								
Young vs. Older	***β***	0.12	0.03	0.06	0.22	0.03	0.07	0.10
	SE	0.12	0.05	0.09	0.14	0.10	0.07	0.18
	t	1.96*	0.67	0.63	1.93	0.30	1.07	0.99
Text Type								
Normal vs. Word-beginning	***β***	0.23	0.10	0.19	0.23	0.21	0.05	0.39
	SE	0.02	0.01	0.01	0.04	0.01	0.01	0.07
	t	16.15*	11.31*	12.97*	6.01*	17.07*	2.73*	5.38*
Normal vs. Internal	***β***	0.13	0.04	0.09	0.09	0.11	0.01	0.17
	SE	0.02	0.01	0.02	0.04	0.01	0.01	0.08
	t	7.42*	5.00*	5.91*	2.49*	8.67*	0.92	2.05*
Normal vs. Word- End	***β***	0.18	0.05	0.13	0.07	0.15	0.05	0.20
	SE	0.02	0.01	0.01	0.03	0.01	0.01	0.07
	t	10.93*	5.93*	9.09*	2.05*	10.86*	3.67*	2.93*
Age x Text Type								
Age x Normal vs. Word-beginning	***β***	0.02	0.01	0.02	0.12	0.02	0.15	0.01
	SE	0.03	0.01	0.03	0.07	0.02	0.03	0.14
	t	0.66	0.89	0.67	1.63	0.67	1.27	0.01
Age x Normal vs. Internal	***β***	0.07	0.01	0.06	0.18	0.04	0.02	60.56
	SE	0.03	0.01	0.03	0.07	0.02	0.02	0.16
	t	1.08	0.76	1.09	1.58	1.53	0.66	0.04
Age x Normal vs. Word-End	***β***	0.02	0.01	0.01	0.07	0.02	0.04	0.10
	SE	0.03	0.02	0.03	0.07	0.03	0.03	0.13
	t	0.64	0.52	0.20	0.94	0.61	1.39	0.76

Experiment 5-log-transformed LMEM statistics

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	Gaze Duration (ms)	Rereading Time (ms)	Total Reading Time (ms)
Intercept	***β***	5.44	0.01	5.53	0.01	5.75
	SE	0.02	0.01	0.02	0.01	0.03
	t/z	297.87*	263.38*	254.49*	173.59*	186.12*
Age						
Young vs. Older	***β***	0.04	0.01	0.02	0.01	0.01
	SE	0.03	0.01	0.04	0.01	0.05
	t/z	1.02	0.92	0.41	1.59	0.26
Critical Word Type						
Experimental vs.	***β***	3.32	0.01	0.01	0.01	0.03
Control	***SE***	2.75	0.01	0.02	0.01	0.02
	t/z	1.19	1.37	0.82	0.95*	1.92
Context						
Neutral vs. Biased	***β***	0.01	0.01	0.01	0.01	0.08
	SE	0.01	0.01	0.02	0.01	0.03
	t/z	0.12	0.87	0.40	1.84*	2.28*
Age x Critical Word Type						
Young vs. Older X	***β***	0.01	0.01	2.74	0.01	0.02
Experimental vs.	***SE***	0.02	0.01	5.74	0.01	0.03
Control	**t/z**	0.68	0.38	0.48	0.08	0.81
Age x. Context						
Young vs. Older X	***β***	0.01	0.01	0.02	0.01	0.03
Neutral vs. Biased	***SE***	0.02	0.01	0.02	0.01	0.03
	t/z	0.26	0.35	0.70	0.90	0.76

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	Gaze Duration (ms)	Rereading Time (ms)	Total Reading Time (ms)
Critical Word Type x Context						
Experimental vs. Control X Neutral vs. Biased	***β***	0.03	0.01	0.02	0.01	0.08
	SE	0.02	0.01	0.03	0.01	0.04
	t/z	1.43	0.01	0.68	2.52*	2.08*
Age x Critical Word Type x Context						
Age X Experimental vs. Control X Neutral vs. Biased	***β***	0.07	0.01	0.03	0.01	0.08
	SE	0.04	0.01	0.05	0.01	0.06
	t/z	1.23	0.03	0.71	1.20	1.30

Experiment 6- log-transformed LMEM statistics.

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	Gaze Duration (ms)	Rereading Time (ms)	Total Reading Time (ms)
Intercept	***β***	4.93	5.02	4.80	0.01	5.70
	SE	0.03	0.03	0.03	0.01	0.03
	t/z	162.74*	171.55*	140.08*	194.43*	194.67*
Age						
Young vs. Older	***β***	0.14	0.11	0.10	0.01	0.10
	SE	0.06	0.05	0.05	0.01	0.05
	t/z	2.44*	2.02	0.58	2.36*	1.94
Critical Word Type						
Experimental vs.	***β***	0.06	0.06	0.05	0.01	0.02
Control	***SE***	0.03	0.05	0.01	0.01	0.01
	t/z	1.58	1.66	0.85	0.26	1.56
Context						
Neutral vs. Biased	***β***	0.03	0.03	0.03	0.01	0.09
	SE	0.03	0.03	0.01	0.01	0.02
	t/z	0.86	1.08	1.74	2.51*	3.68*
Age x Critical Word Type						
Young vs. Older X	***β***	0.02	0.05	0.04	0.01	0.07
Experimental vs.	***SE***	0.04	0.05	0.04	0.01	0.03
Control	**t/z**	0.34	0.98	0.08	1.88	2.64
Age x. Context						
Young vs. Older X	***β***	0.02	0.05	0.01	0.01	0.01
Neutral vs. Biased	***SE***	0.05	0.05	0.05	0.01	0.03
	t/z	0.06	1.03	0.90	1.59	0.31

		First-Fixation Duration (ms)	Single-Fixation Duration (ms)	Gaze Duration (ms)	Rereading Time (ms)	Total Reading Time (ms)
Critical Word Type x Context						
Experimental vs. Control X Neutral vs. Biased	***β***	0.01	0.03	0.01	0.01	0.05
	SE	0.05	0.06	0.02	0.01	0.04
	t/z	0.06	0.54	1.41	2.65*	2.70*
Age x Critical Word Type x Context						
Age X Experimental vs. Control X Neutral vs. Biased	***β***	0.10	0.04	0.03	0.01	0.20
	SE	0.09	0.10	0.05	0.01	0.05
	t/z	1.05	0.42	1.19	2.10*	1.98

Experiment 7-log-transformed LMEM statistics.

Appendix D

Adjusted stimuli used in Experiment 4 and Experiment 5 (the remaining items are the same as White et al., 2008).

```
Sue discovered an unknown dinosaur during her work abroad in Asia.
He described the ancient dinosaur that he studied at university.
Pete climbed to the top of the large trellis and cleaned it.
John was able to repair the broken trellis very quickly.
We were unable to repair the ligament even though we wanted to.
I was sad that my ruined ligament could not be fixed.
Val required some scissors before she could start the project.
Will you bring me the scissors and a pen right away.
Tony was a great educator and took pride in helping people.
Life as a good educator is a rewarding choice for anyone.
Pam picked up the discarded mascara off the dirty carpet.
```

Appendix E

Stimuli used in Experiment 7. A subset of these stimuli are the same as in Slattery, (2009).

In all cases, the neutral sentence is presented first, followed by the biased sentence. Experimental and control words are italicised. The HFN appears in parentheses.

This was the best robe/apron available, according to the salesman. (role)

She purchased the cotton *robe/apron* even though it was very expensive. (role)

The big storm caused the *brunch/buffet* to be cancelled. (branch)

The fantastic food at the *brunch/buffet* was enjoyed by everyone. (branch)

Sadly, the big *shack/cabin* in the woods was destroyed by the strong winds. (shock)

They wanted to live in a *shack/cabin* in the countryside, far from the city. (shock)

Before he had *gene/cell* therapy, he was very concerned about the disease. (gone)

The researcher was examining the *gene/cell* as part of an experiment. (gone)

The very large *choir/chorus* filled the room with a beautiful sound. (chair)

The enthusiasm of the choir/ chorus made the performance very enjoyable. (chair)

The injured old *worm/crab* was not likely to live much longer. (worn)

Before the frightened worm/crab could reach cover, a bird caught it. (worn)

The new and modern lock/knob on the door was very stiff and difficult to open. (look)

The safe had a lock/knob which was ideal for protecting against theft. (look)

The large and expensive *icon/idol* was erected in the church. (iron)

Andrew was considered a local *icon/idol* due to all of his work in the community. (iron)

Unfortunately, the sudden *stroke/injury* resulted in a worse prognosis than first thought. (strike)

John was very ill following his stroke/injury and could not work for some time.

The newspaper reported that the *medic/nurse* had not performed the procedure correctly. (media)

The hospital hired the new *medic/nurse* as he seemed very skilled. (media)

Due to the *herd/pack* of animals in the road, the car was forced to stop. (hard)

The farmer thought that the *herd/pack* was ready to be sent out to pasture. (hard)

The outdated punishment *cane/stick* was no longer in use at the school. (came)

The elderly man walked with a *cane/stick* and moved very slowly. (came)

Tom was very *crass/rude* in his assumptions about people. (cross)

Jane's behaviour was *crass/rude* and all of her friends were embarrassed. (cross)

All of his *stiff/sore* joints made James exceedingly uncomfortable. (stuff)

The patient's knee was stiff/sore and medication was required to treat it. (stuff)

The large and unstable *rack/rail* had not been attached to the roof properly. (rock)

On top of the car they fitted a rack/rail for transporting their bicycles. (rock)

She couldn't take the *pair/pack* with her when she moved office. (pain)

Jane bought a *pair/pack* of oranges to give to her friend. (pain)

He proceeded to *beat/pound* the dirt out of the rug. (heat)

The boxers had to *beat/pound* their opponents to win the trophy. (heat)

The very first *cheek/thumb* that the doctor examined looked very swollen. (check)

She pressed her cheek/thumb against the window pane. (check)

Eventually it became clear, the *sane/wise* thing to do was to leave. (same)

The idea was crazy; I couldn't believe a *sane/wise* person had come up with it. (wise)

Jane said that the good *valve/pipe* would make the water flow much faster. (value)

The plumber fitted a new *valve/pipe* in the old boiler. (value)

Sadly, the left *cornea/retina* of the boy was badly damaged by the branch. (corner)

His vision wouldn't recover after his cornea/retina was damaged. (corner)

She grabbed the string/ribbon and tied it around the tree. (strong)

The length of string/ribbon was holding the package together. (strong)

He did not have enough spice/gravy to perfect the flavour of the dish. (space)

The recipe listed a spice/gravy that I had not used before. (space)

She purchased an expensive new *cloak/scarf* to wear to the dinner party. (clock)

She wore her favourite cloak to keep warm on the cold day.

The strong old *vine/cable* was very sturdy and could support Mary's weight. (wine)

Pat swung from the hanging *vine/cable* and jumped across the lake. (wine)

What a big *farce/sham* the recent vote turned out to be. (force)

The debate turned into a drunken *farce/sham,* much to Tom's disappointment. (force)

To make her *curry/pizza,* Tina needed some more garlic. (carry)

The scent of *curry/pizza* filled the room and made everyone hungry. (carry)

Jane saw the *boot/shoe* in the shop window and wanted it immediately. (boat)

Betty wore the *boot/shoe* when she went skiing in France. (boat)

They thought that the *queer/eerie* looking box belonged to Betty. (queen)

The abandoned hotel looked very creepy and *queer/eerie,* it frightened me. (queen)

The report stated that the ship *mast/hull* was damaged by the waves. (must)

The captain complained that the *mast/hull* was too dirty. (must)

They thought that the *oily/waxy* product was used by the mechanic. (only)

A spillage had made the ground *oily/waxy* and unsafe to walk on. (only)

The worker was a member of the onion/squash growing club. (union)

She fried the *onion/squash* with various spices and put it in the oven. (union)

The engineers built a *truck/lorry* using old car parts. (track)

The tyres on the *truck/lorry* were the best quality available. (track)

I was disappointed that the *filth/urine* on the floor was difficult to remove. (fifth)

I worked hard to remove the *filth/urine* before anyone noticed it. (fifth)

He cleaned the dirty *flour/wheat* from the work surface before finishing the cake. (floor)

The cook ran out of *flour/wheat* and could not bake enough bread. (floor)

The builder used the foam/tube to fill the hole in the wall. (form)

The parcel was packaged using the foam/tube to prevent it breaking. (form)

The rioters began to *hurl/toss* rocks at the police. (hurt)

The talented player could *hurl/toss* the ball a great distance. (hurt)

The end of the *lance/sword* was broken during the battle. (dance)

The warrior held his *lance/sword* tightly and faced the enemy. (dance)

The loud and unpleasant *tune/hymn* was played at the Christmas party. (tone)

They danced to the *tune/hymn* the band were performing. (tone)

It seemed that no *truce/siege* would be successful while the rebels remained hiding. (trace)

A spokesman said the short *truce/siege* had ended unexpectedly. (trace)

They successfully located the *squire/shield* of the brave knight. (square)

The knight found his *squire/shield* and collected this rest of his armour. (square)

Clearly, all the *whale/shark* wanted to do was swim in the ocean. (while)

In the distance we saw a *whale/shark* swimming gracefully. (while)

They held the oddly shaped *moss/weeds* in their hands and searched for wildlife. (mass)

The gardener cleared the *moss/weeds* before planting the flowers. (mass)

The newly developed *skate/bike* was just the right size for my daughter. (state)

The wheels of the *skate/bike* were too loose and needed to be tightened. (state)

Appendix F

A comparison of visually similar and visually dissimilar HFNs from Experiment 6.

Total Reading Time		Neutral Context		Biased Context	
		Experimental	Control	Experimental	Control
Overall	Young	394 (19)	368 (18)	348 (16)	338 (17)
	Older	400 (27)	363 (26)	346 (23)	350(24)
Visually similar	Young	404 (22)	360 (18)	352 (18)	333 (18)
	Older	420 (28)	360 (22)	354 (23)	352 (23)
Visually dissimilar	Young	382 (19)	369 (17)	346 (15)	352 (20)
	Older	381 (27)	371 (27)	343 (22)	362 (26)

References

Abbott, M. J. & Staub, A. (2015). The effect of plausibility on eye movements in reading: Testing the E-Z reader's null predictions. *Journal of Memory and Language, 85,* 76-87.

Adelman, J. S. (2011). Letters in time and retinotopic space. *Psychological Review, 118,* 570-582.

Allen, P. A., Smith, A. F., Lien, M. C., Kaut, K. P., & Canfield, A. (2009). A multi-stream model of visual word recognition. *Attention, Perception, & Psychophysics, 71*, 281-296.

Andrews, S. (1989). Frequency and neighborhood effects on lexical access: Activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 802-814.

Andrews, S. (1992). Frequency and neighborhood effects on lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition,* 18, 234-254.

Andrews, S. (1996). Lexical retrieval and selection processes: Effects of transposed-letter confusability. *Journal of Memory and Language*, *35*, 775-800.

Andrews, S. (1997). The effects of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychological Bulletin & Review*, *4*, 439-461.

Apel, J. K., Henderson, J. M., & Ferreira, F. (2012). Targeting regressions: Do readers pay attention to the left? *Psychonomic Bulletin & Review, 19,* 1108-1113.

Aschenbrenner, A. J., Balota, D. A., Weigand, A. J., Scaltritti, M., & Besner D. (2017). The first letter position effect in visual word recognition: The role of spatial attention. *Journal of Experimental Psychology: Human Perception and Performance, 43,* 700-718.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59,* 390-412.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). The CELEX Lexical Database (Release 2) [CD-ROM]. Philadelphia: Linguistic Data Consortium, University of Pennsylvania.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America. A, Optics and Image Science, 5,* 2210-2219.

Balota, D. A., & Abrams, R. A. (1995). Mental chronometry: Beyond onset latencies in the lexical decision task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1289-1302.

Balota, D. A., Aschenbrenner, A. J., & Yap, M. J. (2013). Additive effects of word frequency and stimulus quality: The influence of trial history and data transformations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39,* 1563-1571.

Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H., & Yap, M. J. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology: General, 133,* 283-316.

Balota, D. A., & Ferraro, F. R. (1993). A dissociation of frequency and regularity effects in pronunciation performance across young adults, older adults, and individuals with senile dementia of the Alzheimer type. *Journal of Memory & Language, 32,* 573-592.

Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology, 17,* 364-390.

Balota, D. A., Yap, M. J., Hutchison, K. A., & Cortese, M. J. (2012). Megastudies: Large scale analysis of lexical processes. In J. S. Adelman (Ed.), *Visual Word Recognition Vol. 1: Models and Methods, Orthography and Phonology*. Hove, England: Psychology Press.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68,* 255–278.

Bates, D., Mächler, M., & Bolker, B. (2011). LME4: linear mixed-effects models using S4 classes. R Package Version 0.999375-39. http://CRAN.R-project.org/package=lme4.

Becker, C. A., & Killion, T. H. (1977). Interaction of visual and cognitive effects in word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 389–401.

Ben-David, B. M., Erel, H., Goy, H., & Schneider, B. A. (2015). “Older is always better”: Age-related differences in vocabulary scores across 16 years. *Psychology and Aging, 30,* 856-862.

Bever, T. G. (1970). The cognitive basis for linguistic structures. In J. R. Hayes (Eds.), *Cognition and the Development of Language.* New York: John Wiley and Sons.

Binder, K. S., Pollatsek, A., & Rayner, K. (1999). Extraction of information to the left of the fixated word in reading. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1162 – 1172.

Blythe, H. I., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2014). Reading transposed text: effects of transposed letter distance and consonant-vowel status on eye movements. *Attention, Perception & Psychophysics, 76,* 2424-2440.

Blythe, H. I., & Joseph, H. S. S. L. (2011). Children’s eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 643–662). Oxford, England: Oxford University Press.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178.

Bouma, H. (1971). Visual recognition of isolated lower case letters. *Vision Research, 11*, 459-474.

Bowles, N.L. & Poon, L.W. (1981). The effect of age on speed of lexical access. *Experimental Aging Research, 7,* 417-426.

Briihl, D., & Inhoff, A. W. (1995). Integrating information across fixations during reading**:** The use of orthographic bodies and of exterior letters. *Journal of Experimental Psychology***:** *Learning, Memory, and Cognition*, *21*, 55–67.

Broerse, A. C, & Zwaan, E. J. (1966). The information value of initial letters in the identification of words. *Journal of Verbal Learning and Verbal Behavior*, *5*, 441-446.

Brysbaert, M., Drieghe, D., & Vitu, F. (2005). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Cognitive Processes in Eye Guidance* (pp. 53-77), Oxford, UK: Oxford University Press.

Brysbaert, M., Keuleers, E., & New, B. (2011). Assessing the usefulness of Google Books' word frequencies for psycholinguistic research on word processing. Frontiers in Psychology, 2:27.

Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41,* 977-990.

Brysbaert, M., Stevens, M., Mandera, P., & Keuleers, E. (2016) How many words do we know? Practical estimates of vocabulary size dependent on word definition, the degree of language input and the participant's age. *Frontiers in Psychology, 7(1116).*

Brysbaert, M., & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Eye Guidance in Reading and Scene Perception* (pp. 125-147). Oxford, UK: Elsevier.

Calabrèse, A., Cheong, A., Cheung, S-H., He, Y., Kwon, M., Mansfield, J. S., Subramanian, A., Yu D., Legge, G. E. (2016) Baseline MNREAD measures for normally sighted subjects from childhood to old age. *Investigative ophthalmology & visual Science, 57,* 3836-3843.

Cai, Q. & Brysbaert, M. (2010). SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *PLOS ONE, 5,* e10729.

Carr, T. H., Lehmkuhle, S. W., Kottas, B., Astor-Stetson, E. C., & Arnold, D. (1976). Target position and practice in the identification of letters in varying contexts: A word superiority effect. *Perception & Psychophysics, 19,* 412–416.

Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in Cognitive Sciences, 18,* 90-98.

Charness, N., Dijkstra, K. (1999). Age, luminance, and print legibility in homes, offices, and public places. *Human Factors, 41,* 173-193.

Chen, S. P., Bhattacharya, J., & Pershing, S. (2017). Association of vision loss with cognition in older adults. *JAMA Ophthalmology, 135*, 963-970.

Choi, W., Lowder, M. W., Ferreira, F., & Henderson, J. M. (2015). Individual differences in the perceptual span during reading: Evidence from the moving window technique. *Attention, Perception, & Psychophysics, 77*, 2463-2475.

Choi, W., Lowder, M. W., Ferreira, F., Swaab, T. Y., & Henderson, J. M. (2017). Effects of word predictability and preview lexicality on eye movements during reading: A comparison between young and older adults. *Psychology and Aging, 32*, 232-242.

Christianson, K., Johnson, R. L., & Rayner, K. (2005). Letter transpositions within and across morphemes. *Journal of Experimental Psychology**:** Learning, Memory, and Cognition*, *31*, 1327–1339.

Clark, H. H. (1973). The language-as-fixed-effect fallacy: A critique of language statistics in psychological research. *Journal of Verbal Learning and Verbal Behavior*, *12,* 335-359.

Clark, J. J., & O'Regan, J. K. (1999). Word ambiguity and the optimal viewing position in reading. *Vision Research, 39,* 843–857.

Clifton, C., Jr., & Staub, A. (2011). Syntactic influences on eye movements in reading. In: S. P. Liversedge, I. D. Gilchrist & S. Everling (Eds.), *The Oxford Handbook of Eye Movements* (pp. 895-909). Oxford, UK: Oxford University Press.

Clifton, C., Jr., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. In: van Gompel, R. P. G., Fischer, M. H., Murray, W. S., & Hill, R. L. (Eds). *Eye movements: A window on mind and brain.* Elsevier; Amsterdam: 2007.

Cohen-Shikora, E. & Balota, D. A. (2016). Visual word recognition across the adult lifespan. *Psychology and Aging, 31,* 488-502.

Collins, M. J., Brown, B., & Bowman, K. J. (1989). Peripheral visual acuity and age. *Ophthalmic & Physiological Optics, 9,* 314-316.

Coltheart, M., Davelaar, E., Jonasson, J. F., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), Attention & Performance VI (pp. 535-555). Hillsdale, NJ: Erlbaum.

Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001). DRC: A Dual Route Cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108,* 204-256.

Crassini, B., Brown, B., & Bowman, K. (1988). Age-related-changes in contrast sensitivity in central and peripheral retina. *Perception, 17*, 315-332.

Cuetos, F., Glez-Nosti, M., Barbon, A., & Brysbaert, M. (2011). SUBTLEX-ESP: Spanish word frequencies based on film subtitles. *Psicologica, 32,* 133-143.

Daneman, M. & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review, 3,* 422-433.

Davis, C. J. (1999). *The Self-Organising Lexical Acquisition and Recognition (SOLAR) model of visual word recognition*. Unpublished doctoral dissertation, University of New South Wales, Sydney, Australia.

Davis, C. J. (2003). Factors underlying masked priming effects in competitive network models of visual word recognition. In S. Kinoshita, & S.J. Lupker (Eds.), M*asked priming: The state of the art* (pp. 121–170). Hove, UK: Psychology Press.

Davis, C. J. (2005). N-Watch: A program for deriving neighborhood size and other psycholinguistic statistics. Behavior Research Methods, 37, 65-70.

Davis, C. J. (2010). The spatial coding model of visual word identification. Psychological Review, 117, 713-758.

Davis, C. J., & Bowers, J. S. (2006). Contrasting five different theories of letter position coding: Evidence from orthographic similarity effects. *Journal of Experimental Psychology: Human Perception and Performance*, *32,* 535-557.

Davis, C. J. & Lupker, S. J. (2006). Masked inhibitory priming in English: Evidence for lexical inhibition. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 668-687.

Department for Work & Pensions (2013). Older workers statistical information booklet 2013: Official statistics.

Deutsch, A., Frost, R., Pelleg, S., Pollastek, A., & Rayner, K. (2003). Early morphological effects in reading: Evidence from parafoveal preview benefit in Hebrew. *Psychonomic Bulletin & Review, 10*, 415-422.

Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2005). Morphological parafoveal preview benefit effects in reading: Evidence from Hebrew. *Language and Cognitive Processes, 20*, 341-371.

Dimitropoulou, M., Duñabeitia, J. A., Avilés, A., Corral, J., & Carreiras, M. (2010). Subtitle-Based Word Frequencies as the Best Estimate of Reading Behavior: The Case of Greek. *Frontiers in Psychology, 1.*

Drieghe, D. (2008). Foveal processing and word skipping during reading. *Psychonomic Bulletin & Review, 15*, 856–860.

Drieghe, D., Brysbaert, M., Desmet, T., & De Baecke, G. (2004). Word skipping in reading: On the interplay of linguistic and visual factors. *European Journal of Cognitive Psychology, 16,* 79-103.

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance,* 31, 954-969.

Edwards, J. D., Ross, L. A., Wadley, V. G., Clay, O. J., Crowe, M., Roenker, D. L., & Ball, K. K. (2006). The useful field of view test: Normative data for older adults. *Archives of Clinical Neuropsychology, 21*, 275-286.

Elliott, D., Whitaker, D., & MacVeigh, D. (1990). Neural contribution to spatiotemporal contrast sensitivity decline in healthy aging eyes. *Vision Research, 30,* 541-547.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42*, 621-636.

Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112*, 777–813.

Federmeier, K. D., & Kutas, M. (2005). Aging in context: Age-related changes in context use during language comprehension. *Psychophysiology, 42*,133-141.

Federmeier, K. D., Kutas, M., & Schul, R. (2010) Age-related and individual differences in the use of prediction during language comprehension. *Brain & Language, 115*, 149-161.

Fernández, G., Schumacher, M., Castro, L., Orozco, D., Agamennoni, O. (2015). Patients with mild Alzheimer’s disease produced shorter outgoing saccades when reading sentences. *Psychiatry Research, 229.*

Fernández, G., Mandolesi, P., Rotstein, N., Colombo, O., Agamennoni, O., & Politi, L. (2013). Eye movement alterations during reading in patients with early Alzheimer disease. *Investigative Ophthalmology & Visual Science, 54*.

Fernández, G., Manes, F., Rotsein, N. P., Colombo, O., Mandolesi, P., Politi, L. E., & Agamennoni, O. (2014). Lack of contextual-word predictability during reading in patients with mild Alzheimer disease. *Neuropsychologia, 62,* 143–151.

Ferris, F. L., & Bailey, I. L. (1996). Standardizing the measurement of visual acuity for clinical research studies. *Ophthalmology, 103*, 181-182.

Findlay, J. M., & Gilchrist, I. D. (2003) *Active vision: The psychology of looking and seeing*. Oxford, UK: Oxford University Press.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioural and Brain Sciences, 22(4)*, 661-674.

Fitzsimmons, G., & Drieghe, D. (2013). How fast can predictability influence word skipping during reading? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39,* 1054-1063.

Forster, K. I. (1976). Accessing the mental lexicon. In R. J.Wales & E.Walker (Eds.), *New approaches to language mechanisms*. Amsterdam: North-Holland.

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology, 39A*, 211-251.

Fox, J., Friendly, M., & Weisberg, S. (2013). Hypothesis tests for multivariate linear models using the car package. *R Journal, 5(1),* 39-52.

Frost, R. (2015). Cross-linguistic perspectives on letter-order processing-Empirical findings and theoretical considerations. In A. Pollatsek & R. Treiman (Eds.). *The Oxford Handbook of Reading* (pp. 88-98). New York: Oxford University Press.

Gagl, B., Hawelka, S., Richlan, F., Schuster, S., & Hutzler, F. (2014). Parafoveal preprocessing in reading revisited: evidence from a novel preview manipulation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 40*, 588-595.

Gillespie-Gallery, H., Konstantakopoulou, E., Harlow, J. A., & Barbur, J. L. (2013). Capturing age-related changes in functional contrast sensitivity with decreasing light levels in monocular and binocular vision. *Investigative Ophthalmology & Visual Science, 54,* 6093-6103.

Glaholt, M. G., Rayner, K., & Reingold, E. M. (2014). A rapid effect of stimulus quality on the durations of individual fixations during reading. *Visual Cognition, 22,* 377-389.

Gómez, P., Ratcliff, R. & Perea, M. (2008). *The overlap model:* a model of letter position coding. *Psychological Review,* 115(3) 577-600.

Gómez, P., Ratcliff, R. & Perea, M. (2008). The overlap model: a model of letter position coding. *Psychological Review, 115,* 577-600.

Grabbe, J. W., & Allen, P. A. (2013). Age-related sparing of parafoveal lexical processing. *Experimental Aging Research, 39*, 419-444.

Grainger, J., Bertrand, D., Lété, B., Beyersmann, E., & Ziegler, J.C. (2016). A developmental investigation of the first letter advantage. *Journal of Experimental Child Psychology, 152,* 161-172.

Grainger, J., & Jacobs, A. M. (1994). A dual read-out model of word context effects in letter perception: Further investigations of the word superiority effect. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1158-1176.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, *103*, 518-565.

Grainger, J., Lété, B., Bertrand, D., Dufau, S., & Ziegler, J.C. (2012). Evidence for multiple routes in learning to read. *Cognition*, 123, 280-292.

Grainger, J., Tydgat, I., & Issele, J. (2010). Crowding affects letters and symbols differently. *Journal of Experimental Psychology: Human Perception and Performance, 36*, 673-688.

Grainger, J., & van Heuven, W. J. B. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *Mental lexicon: "Some words to talk about words"* (pp. 1–24). New York: Nova Science Publishers.

Grainger, J., & Whitney, C. (2004). Does the human mind raed words as a wlohe? *Trends in Cognitive Sciences, 8*, 58–59.

Gregg, J., & Inhoff, A. W. (2016). Misperception of orthographic neighbours during silent and oral reading. *Journal of Experimental Psychology: Human Perception and Performance*, 42, 799-820.

Guérard K, Saint-Aubin J, Poirier M, Demetriou C. (2012). Assessing the influence of letter position in reading normal and transposed texts using a letter detection task. *Canadian Journal of Experimental Psychology, 66(4),* 227-238.

Häikiö, T. *Bertram*, R. *Hyönä*, J. Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology, 102*, 167–181.

Hand, C. J., O'Donnell, P. J., & Sereno, S. C. (2012). Word-initial letters influence fixation durations during fluent reading. *Frontiers in Psychology*, *3* (85), 1-19.

Hansen, D., & Ji, Q. (2010). In the eye of the beholder: A survey of models for eyes and gaze. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(3),* 478–500.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention & Performance, XVII, Cognitive Regulation of Performance: Interaction of Theory and Application* (pp. 653-675). Massachusetts, USA: MIT Press.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory and Cognition, 16(3)*, 417-429.

Hohenstein, S., Laubrock, J., & Kliegl, R. (2010). Semantic preview benefit in eye movements during reading: A parafoveal fast-priming study. Journal of Experimental Psychology: Learning, Memory, and Cognition, 36, 1150-1170.

Hohenstein S., & Kliegl R. (2013). Eye movements reveal interplay between noun class and word capitalization in reading. In: Knauff M, Pauen M, Sebanz N, Wachsmuth I, editors. Proceedings of the 35th Annual Conference of the Cognitive Science Society. Austin, TX: Cognitive Science Society; 2013. pp. 2554-2559.

Hohenstein S., & Kliegl R. (2014). Semantic preview benefit during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 166-190.

Huaman, A.G., & Sharpe, J. A. (1993). Vertical saccades in senescence. *Investigative Ophthalmology & Visual Science, 34,* 2588-2595.

Huey, E. B. (1908). *The psychology and pedagogy of reading*. New York, USA: Macmillan.

Hyönä, J. (2011). Foveal and parafoveal processing during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), Oxford library of psychology. *The Oxford handbook of eye movements* (pp. 819-838). New York: Oxford University Press.

Inhoff, A. W., & Rayner, K. (1986) Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40*. 431-439.

Inhoff, A. W., Starr, M., Liu, W., & Wang, J. (1998). Eye-movement-contingent display changes are not compromised by flicker and phosphor persistence. *Psychonomic Bulletin & Review, 5*, 101-106.

Jacobs, A. M. & Grainger, J. (1992). Testing a semistochastic variant of the interactive activation model in different word recognition experiments. *Journal of Experimental Psychology: Human Perception and Performance*, *18,* 1174-1188.

Jainta, S., Nikolova, M., & Liversedge, S. P. (2017). Does text contrast mediate binocular advantages in reading? *Journal of Experimental Psychology: Human Perception and Performance, 43*, 55-68.

Johnson, R. L. (2009). The quiet clam is quite calm: Transposed-letter neighborhood effects on eye movements during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 943-969.

Johnson, R. L., & Dunne, M. D. (2012). Parafoveal processing of transposed-letter words and nonwords: Evidence against parafoveal lexical activation. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 191-212.

Johnson, R. L., & Eisler, M. E. (2012). The importance of first and last letter in words during sentence reading. *Acta Psychologica, 141*, 336-351.

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading**:** Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 209–229.

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2014). Reading with filtered fixations: Adult age differences in the effectiveness of low-level properties of text within central vision. *Psychology and Aging, 29*, 229-235.

Juhasz, B. J., & Rayner, K. (2003). Investigating the effects of a set of intercorrelated variables on eye fixation durations in reading. *Journal of Experimental Psychology: Learning, Memory and Cognition, 29,* 1312-1318.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87,* 329–35.

Kambe, G. (2004). Parafoveal processing of prefixated words during eye fixations in reading: Evidence against morphological influences on parafoveal preprocessing. *Perception & Psychophysics, 66,* 279-292.

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association, 90*, 773-795.

Katz, L., Brancazio, L., Irwin, J., Katz, S., Magnuson, J. &, Whalen, D.H. (2011). What lexical decision and naming tell us about reading. *Reading and Writing, 25,* 1259-1282.

Kemper, S., Crow, A., & Kemtes, K. (2004). Eye-Fixation Patterns of High- and Low-Span Young and Older Adults: Down the Garden Path and Back Again. *Psychology and Aging, 19,* 157-170.

Kemper, S. & Liu, C. J. (2007). Eye movements of young and older adults during reading. *Psychology and Aging, 22,* 84-93.

Kemper, S., & McDowd, J. (2006). Eye movements of young and older adults while reading with distraction. *Psychology and Aging*, 21, 32-39.

Kemper, S., McDowd, J., Metcalf, K., & Liu, C. J. (2008). Young and older adults' reading of distracters. *Educational Gerontology, 34,* 489-502.

Kennedy, A. (1998). The influence of parafoveal words on foveal inspection time: Evidence for a processing trade-off. In: G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 149-179). BV, Netherlands: Elsevier.

Kennedy, A. & Pynte, J. (2005), Parafoveal-on-foveal effects in normal reading. *Vision Research, 45,* 153-168.

Kerber, K. A., Ishiyama, G. P., & Baloh, R. W. (2006). A longitudinal study of oculomotor function in normal older people. *Neurobiology of Aging, 27*, 1346-1353.

Keuleers, E., Brysbaert, M., & New, B. (2010). SUBTLEX-NL: A new frequency measure for Dutch words based on film subtitles. *Behavior Research Methods, 42*, 643-650.

Keuleers, E., Stevens. M., Mandera, P., & Brysbaert, M. (2015). Word knowledge in the crowd: Measuring vocabulary size and word prevalence in a massive online experiment. *The Quarterly Journal of Experimental Psychology*, *68*, 1665-1692.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology*, *16*, 262-284.

Kneale, D. (2012). *Is social exclusion still important for older people?* London, UK: The International Longevity Centre – UK.

Kosnik, W., Winslow, L., Kline, D., Rasinski, K., & Sekuler, R. (1988). Visual changes in daily life throughout adulthood. *Journals of Gerontology, 43,* 63-70.

Kretzschmar, F., Schlesewsky, M., & Staub, A. (2015). Dissociating word frequency and predictability effects in reading: Evidence from coregistration of eye movements and EEG. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 1648-1662.

Ktori, M., Kingma, B., Hannagan, T., Holcomb, P. J., Grainger, J. (2014). On the time-course of adjacent and non-adjacent transposed-letter priming. *Journal of Cognitive Psychology, 26,* 491-505.

Laitinen, A., Koskinen, S., Harkanen, T., Reunanen, A., Laatikainen, L., & Aromaa, A. (2005). A nationwide population-based survey on visual acuity, near vision, and self-reported visual function in the adult population in Finland. *Ophthalmology, 112*, 2227-2237.

Laubrock, J., Kliegl, R., & Engbert, R. (2006). SWIFT explorations of age differences in eye movements during reading. *Neuroscience and Biobehavioral Reviews, 30,* 872-884.

Legge, G. E., Rubin, G. S., Pelli, D. G., Schleske, M. M. (1985). Psychophysics of reading. II. Low vision. *Vision Research*, 25, 253–265.

Levi, D. M. (2008). Crowding-an essential bottleneck for object recognition: a mini-review. *Vision research, 48,* 635-654.

Levitt, J. B., & Lund, J. S. (1997). Contrast dependence of contextual effects in primate visual cortex. *Nature, 387,* 73–76.

Lima, S. D., and Inhoff, A. W. (1985). Lexical access during eye fixations in reading: effects of word-initial letter sequence. *Journal of Experimental Psychology: Human Perception and Performance*. *11*, 272–285.

Liu, P., Li, X., Han, B. (2015). Additive effects of visual quality and word frequency on eye movements during Chinese reading. *Reading and Writing, 28,* 199-215.

Liu, Z., Pan, Y., Tong, W., & Liu N. (2017). Effects of adults aging on word encoding in reading Chinese: evidence from disappearing text. *PeerJ*, e2897.

Liversedge, S. P., Drieghe, D., Li, X., Yan, G., Bai, X., & Hyönä, J. (2016). Universality in eye movements and reading: A trilingual investigation. *Cognition, 147,* 1-20.

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences, 4(1),* 6-14.

Liversedge, S. P., Paterson, K. B., & Pickering, M. J. (1998) Eye movements and measures of reading time. In: G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 55-75). BV, Netherlands: Elsevier.

Lupker, S. J. (2005). Visual Word Recognition: Theories and Findings. In M. J. Snowing & C. Hulme (Eds.), *The Science of Reading: A Handbook* (pp. 39-60). New Jersey, USA: Wiley-Blackwell.

Madden, D.J. (1988). Adult age differences in the effects of sentence context and stimulus degradation during visual word recognition. *Psychology and Aging, 3*, 167-172.

Marcet, A., & Perea, M. (2017). Is nevtral NEUTRAL? Visual similarity effects in the early phases of written-word recognition. *Psychonomic Bulletin and Review, 24,* 1180-1185.

Marcet, A., & Perea, M. (in press). Can I order a burger at rnacdonalds.com? Visual similarity effects of multi-letter combinations at the early stages of word recognition. *Journal of Experimental Psychology: Learning, Memory and Cognition.*

Marx C., Hawelka S., Schuster S., Hutzler F. (2015). An incremental boundary study on parafoveal preprocessing in children reading aloud: parafoveal masks overestimate the preview benefit. *Journal of Cognitive Psychology, 27,* 549-561.

Marx, C., Hutzler, F., Schuster, S., & Hawelka, S. (2016). On the Development of Parafoveal Preprocessing: Evidence from the Incremental Boundary Paradigm. *Frontiers in Psychology,* 7*,* 514.

Matin, E. (1974). Saccadic suppression: a review and analysis. *Psychological Bulletin, 81*, 899-917.

McArthur, A. D., Sears, C. R., Scialfa, C. T., & Sulsky, L. M. (2015). Aging and the inhibition of competing hypotheses during visual word identification: evidence from the progressive demasking task. *Aging, Neuropsychology, and Cognition, 22*, 220-243.

McCandliss, B. D., Cohen, L., & Dehaene S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7,* 293-299.

McCarley, J. S., Yamani, Y., Kramer, A. F., & Mounts, J. R. W. (2012). Age, clutter, and competitive selection. *Psychology and Aging*, *27*, 616-626.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review*, *86,* 287-330.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review*, *88*, 375–407.

McConkie, G. W., Kerr, P.W., Reddix, M.D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics, 46*, 245-253.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578-586.

McConkie, G., & Rayner, K. (1976). Asymmetry of perceptual span in reading. *Bulletin of the Psychonomic Society, 8,* 365-368.

McCutchen, D., & Perfetti, C. A. (1982). The visual tongue-twister effect: Phonological activation in silent reading. *Journal of Verbal Learning and Verbal Behavior, 21*, 672-687.

McDonald, S. A., Carpenter, R. H., & Shillcock, R. C. (2005). An anatomically constrained, stochastic model of eye movement control in reading. *Psychological Review, 112,* 814-840.

McGowan, V. A., White, S. J., Jordan, T. R., & Paterson, K. B. (2014). Aging and the use of interword spaces during reading: Evidence from eye movements. *Psychonomic Bulletin & Review, 21*, 740-747.

McGowan, V. A., White, S. J., & Paterson, K. B. (2015). The effects of interword spacing on the eye movements of young and older readers. *Journal of Cognitive Psychology*, *27*, 609-621.

Meyer, D. E., Schvaneveldt, R. W., & Ruddy, M. G. (1975). Loci of contextual effects on visual word-recognition. In P. M. A. Rabbitt (Ed.), Attention and performance V. London: Academic Press.

Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science, 20*, 721-728.

Miellet, S., & Sparrow, L. (2004). Phonological codes are assembled before word fixation: Evidence from boundary paradigm in sentence reading. *Brain and Language, 90*, 299-310.

Mitzer, T. L., & Rogers, W. A. (2006). Reading in the dark: Effects of age and contrast on reading speed and comprehension. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *48*, 229-240.

Mund, I., Bell, R., & Buchner, A. (2010). Age differences in reading with distraction: Sensory or inhibitory deficits? *Psychology and Aging, 25*, 886-897.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53,* 695-699.

New, B., Brysbaert, M., Veronis, J., & Pallier, C. (2007). The use of film subtitles to estimate word frequencies. *Applied Psycholinguistics, 28,* 661-677.

Norris, D., Kinoshita, S., & van Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language, 62,* 254-271.

Office for National Statistics (2017). Overview of the UK population: July 2017.

O'Malley, S., Reynolds, M., & Besner, D. (2007). Qualitative differences between the joint effects of visual quality and word frequency in lexical decision and reading aloud: Extensions to Yap and Balota. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 451-458.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (Vol. 4 of Reviews of Oculomotor Research, pp. 395–453). BV, Netherlands: Elsevier.

Owsley, C. (2011). Aging and vision. *Vision Research, 51*, 1610-1622.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23,* 689-699.

Park, D. C., Smith, A. D., Lautenschlager, G., Earles, J. L., Frieske, D., Zwahr, M., & Gaines, C. L. (1996). Mediators of long-term memory performance across the life span. *Psychology and Aging, 11*, 621-37.

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013a). Filtered text reveals adult age differences in reading: Evidence from eye movements. *Psychology and Aging, 28*, 352-364.

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013b). Effects of adult aging on reading filtered text: Evidence from eye movements. *PeerJ, 1*:e63.

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013c). Aging and the control of binocular eye movements during reading. *Psychology and Aging, 28,* 789-795.

Paterson, K. B., Read J., McGowan, V. A., & Jordan, T. R. (2015). Children and adults both see "pirates" in "parties": Letter-position effects for developing readers and skilled adult readers. *Developmental Science*, 18, 335–343.

Payne, B. R. & Stine-Morrow, E. A. L. (2012). Aging, parafoveal preview, and semantic integration in sentence processing: Testing the cognitive workload of wrap-up. *Psychology and Aging, 27,* 638-649.

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7,* 1-36.

Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences, 2*, 187-199.

Perea, M., & Estévez, A. (2008). Transposed-letter similarity effects in naming pseudowords: Evidence from children and adults. *European Journal of Cognitive Psychology*, *20,* 33-46.

Perea, M., & Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain and Language*, *97,* 102-109.

Perea, M., Jimenez, M., & Gomez, P. (2016). Does location uncertainty in letter position coding emerge because of literacy training? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42,* 996–1001.

Perea, M., & Lupker, S. J. (2003a). Does jugde activate COURT? Transposed-letter similarity effects in masked associative priming. *Memory & Cognition*, *31*, 829–841.

Perea, M., & Lupker, S. J. (2003b). Transposed-letter confusability effects in masked form priming. In S. Kinoshita and S. J. Lupker (Eds.), *Masked priming: The state of the art* (pp. 97–120). New York: Psychology Press.

Perea, M., & Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language*, *51*, 231–246.

Perea, M., Palti, D., & Gómez, P. (2012). Associative priming effects with visible, transposed-letter nonwords: JUGDE facilitates COURT. *Attention, Perception, & Psychophysics*, *74*, 481-488.

Perea M. & Panadero, V. (2014). Does viotin activate violin more than viocin? On the use of visual cues during visual-word recognition. *Experimental Psychology*, *61,* 23-29.

Perea, M., & Pollatsek, A. (1998). The effects of neighborhood frequency in reading and lexical decision. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 767-779.

Perea, M., Rosa, E., & Gómez, C. (2005). The frequency effect for pseudowords in the lexical decision task. *Perception and Psychophysics*, *67*, 301–314.

Plourde, C.E., & Besner, D. (1997). On the locus of the word frequency effect in visual word recognition. *Canadian Journal of Experimental Psychology, 51,* 181-194.

Pollastek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in perceptual span for Israeli readers. *Brain and Language, 14*, 174-180.

Pollatsek, A., Lesch, M., Morris R. K. & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of experimental Psychology: Human perception and performance, 18*, 148-162.

Pollatsek, A., Perea, M., & Binder, K. (1999). The effects of neighborhood size in reading and lexical decision. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1142-1158.

R Core Team (2015). R: A language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. <http://www.R-project.org>.

Rawlinson, G. E. (1999). Reibadailty. *New Scientist, 162*, 55.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85*, 618-660.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8*, 21-30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search, *The Quarterly Journal of Experimental Psychology*, *62*,1457-1506.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science, 206*, 468-469.

Rayner, K., Binder, K. S., Ashby, J., & Pollastek, A. (2001). Eye movement control in reading: word predictability has little influence on initial landing positions in words. *Vision Research, 41*, 943-954.

Rayner, K., Castelhano, M. S., & Yang, J. (2009). Eye movements and the perceptual span in older and younger readers. *Psychology and Aging, 24*, 755-760.

Rayner, K., Castelhano, M. S., & Yang, J. (2010). Preview benefit during eye fixations in reading for older and younger readers. *Psychology and Aging, 25*, 714-718.

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 13*, 191-201.

Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: eye movements during reading and scanning are different. *Perception & Psychophysics¸58(5)*, 734-747.

Rayner, K., & Kaiser, J. S. (1975). Reading mutilated text**.** *Journal of Educational Psychology***,** *67,* 301–306.

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino-Perez, D. (2003). Reading disappearing text: Cognitive control of eye movements. *Psychological Science, 14*, 385-388.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research, 46,* 310-323.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading.* Englewood Cliffs, NJ; Prentice Hall.

Rayner, K., Reichle, E. D., Stroud, M., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging, 21,* 448-465.

Rayner, K., & Schotter, E. R. (2014). Semantic preview benefit in reading English: The effect of initial letter capitalisation. *Journal of Experimental Psychology: Human Perception and Performance*, *40,* 1617-1628.

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: a comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 1188-1200.

Rayner, K., Slattery, T. J., Drieghe, D., & Liversedge, S. P. (2011). Eye movements and word skipping during reading: Effects of word length and predictability. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 514-528.

Rayner, K. and Well, A. D. (1996) Effects of Contextual Constraint on Eye Movements in Reading A Further Examination. *Psychonomic Bulletin & Review, 3,* 504-509.

Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31,* 537-550.

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Raeding wrods with jubmled lettres: There is a cost. *Psychological Science*, *17*, 192–193.

Rayner, K., Yang, J., Castelhano, M. S., & Liversedge, S. P. (2011). Eye movements of older and younger readers when reading disappearing text. *Psychology and aging*, *26*, 214-23.

Rayner, K., Yang, J., Schuett, S., & Slattery, T. J. (2013). Eye movements of older and younger readers when reading unspaced text. *Experimental Psychology, 60*, 354-361.

Rayner, K., Yang, J., Schuett, S., & Slattery, T. J. (2014). The effect of foveal and parafoveal masks on the eye movements of older and younger readers. *Psychology and Aging, 29*, 205-212.

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81*, 275-280.

Reichle, E. D. (2011) Serial attention models of reading. In: S.P. Liversedge, I. D. Gilchrist & S. Everling (Eds.), *Oxford Handbook on Eye Movements* (pp. 767-786). Oxford, UK: Oxford University Press.

Reichle, E. D. (2015). Computational modeling of reading: The "whole burrito". In U. Ansorge, T. Ditye, A. Florack, & H. Leder (Eds.), *Abstracts of the 18th European Conference on Eye Movements*, 16-21 August 2015, in Vienna, Austria. Journal of Eye Movement Research.

Reichle, E. D., & Drieghe, D. (2013). Using E-Z reader to examine skipping during reading. *Journal of Experimental Psychology: Learning Memory and Cognition, 39*, 1311-1320.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105*, 125-157.

Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E-Z Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research, 7*, 4-22.

Reichle, E. D., Pollatsek, A., & Rayner, K. (2012). Using E-Z Reader to simulate eye movements in nonreading tasks: A unified framework for understanding the eye-mind link. *Psychological Review, 119,* 155–185.

Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research, 39*, 4403-4411.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26*, 445-476.

Reilly, R., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research, 7,* 34–55.

Reingold, E.M., & Rayner, K. (2006). Examining the word identification stages hypothesized by the E-Z Reader model. *Psychological Science, 17*, 742-746.

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from survival analysis of fixation durations. *Cognitive Psychology, 65,* 177–206.

Risse, S., & Kliegl, R. (2011). Adult age differences in the perceptual span during reading. *Psychology and Aging, 26,* 451-460.

Robert, C., & Mathey, S. (2007). Aging and lexical inhibition: The effect of orthographic neighborhood frequency in young and older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *62*, 340-352.

Rogers, M. A. M., & Langa, K. M. (2010). Untreated poor vision: A contributing factor to late-life dementia. *American Journal of Epidemiology, 171*, 728-735.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology, 56*, 356–374.

Salthouse, T. A. (1984). Effects of age and skill in typing. *Journal of Experimental Psychology*, *13*, 345-371.

Salthouse, T. A. (1994). How many causes are there of aging-related decrements in cognitive functioning? *Developmental Review, 14*, 413- 437.

Salthouse, T. A. (1995b). Influence of processing speed on adult age differences in learning. *Swiss Journal of Psychology, 54*, 102-112.

Salthouse, T. A (1996). The processing speed theory of cognitive aging. *Psychological Review, 103*, 403-428.

Salvucci, D. (2001). An integrated model of eye movements and visual encoding. *Cognitive Systems Research, 1,* 201–220.

Sanford, A. J., & Sturt, P. (2002). Depth of processing in language comprehension: Not noticing the evidence. *Trends in Cognitive Sciences, 6,* 382-386.

Schefrin, B. E., Tregaer, S. J., Harvey, L. O., & Werner, J. S. (1999). Senescent changes in scotopic contrast sensitivity. *Vision Research, 39,* 3728-3726.

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. Language and Cognitive Processes, 19, 333–367.

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention Perception & Psychophysics, 74,* 5-35.

Schotter, E. R., Lee, M., Reiderman, M., Rayner, K. (2015). The effect of contextual constraint on parafoveal processing in reading. *Journal of Memory and Language, 83,* 118-139.

Schroeder, P.J. (2014). The effects of age on processing and storage in working memory span tasks and reading comprehension. *Experimental Aging Research, 40,* 308-331.

Schroeder, S., Hyönä, J., & Liversedge, S. P. (Eds.). (2015). Developmental eye-tracking research in reading [Special issue]. *Journal of Cognitive Psychology,* 27.

Schroeder, S., Eilers, S., & Tiffin-Richards, S. (2018). Investigating eye-movements across the lifespan: Findings from the Berlin DevTrack study [Abstract]. *Experimental Psychology Society,* Leicester, UK.

Schröter, P., & Schroeder, S. (2017). The Developmental Lexicon Project: A behavioral database to investigate visual word recognition across the lifespan. *Behavior Research Methods, 49,* 2183-2203.

Scialfa, C. T., Cordazzo, S., Bubric, K., & Lyon, J. (2013). Aging and visual crowding. *Journals of Gerontology Series B: Psychological Sciences and Social Science, 6,* 522-528.

Sekuler, R., & Ball, K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America. A, Optics and Image Science, 3, 864*-867.

Shake, M. C., & Stine-Morrow, E. A. (2011). Age differences in resolving anaphoric expressions during reading. *Neuropsychology, Development and Cognition, 18,* 678-707.

Sharpe, J. A., & Zackon, D. H. (1987). Senescent saccades. Effects of aging on their accuracy, latency and velocity. *Acta Oto-Laryngologica, 104,* 422–428.

Shen, D., Bai, X., Yan, G., & Liversedge, S. (2009). The perceptual span in Chinese reading. In, K. Rayner, D. Shen, X. Bai & G. Yan (Eds.) *Cognitive and Cultural Influences on Eye Movements* (pp. 255-276). Abingdon, UK: Psychology Press.

Sheridan, H., & Reichle, E. D. (2016). An analysis of the time course of lexical processing during reading. *Cognitive Science, 40,* 522-553.

Sheridan, H., & Reingold, E. M. (2013). A further examination of the lexical processing stages hypothesized by the E-Z Reader model. *Attention, Perception, & Psychophysics, 75,* 407–414.

Slattery, T. J. (2009). Word misperception, the neighbor frequency effect, and the role of sentence context: Evidence from eye movements. *Journal of Experimental Psychology: Human, Perception and Performance*, *35,* 1969-1975.

Soederberg Miller, L. M. (2009). Age differences in the effects of domain knowledge on reading efficiency. *Psychology and Aging*, 24, 63-64.

Sommers, M. S., & Danielson, S. M. (1999). Inhibitory processes and spoken word recognition in young and older adults: The interaction of lexical competition and semantic context. *Psychology and Aging*, *14*, 458-472.

Speranza, F., Daneman, M., & Schneider, B. A. (2000). How aging affects the reading of words in noisy backgrounds. *Psychology and Aging, 15*, 253–258.

Spieler, D. H., & Balota, D. A. (2000). Factors influencing word naming in younger and older adults. *Psychology and Aging, 15,* 225-231.

Stanners, R. F., Jastrzembski, J. E., & Westbrook, A. (1975). Frequency and visual quality in a word-nonword classification task. *Journal of Verbal Learning and Verbal Behavior, 14,* 259-264.

Stanners, R., Neisser, J., Hernon, W., & Hall, R. (1979). Memory representation for morphologically related words. *Journal of Verbal Learning and Verbal Behavior, 21,* 704-721.

Staub, A. (2011). Word recognition and syntactic attachment in reading: Evidence for a staged architecture. *Journal of Experimental Psychology: General, 140,* 407–433.

Sternberg, S. (1969) The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II. Acta Psychologica*, *30,* 276-315.

Stine-Morrow, E. A. L., Loveless, M. K., & Soederberg, L. M. (1996). Resource allocation in on-line reading by younger and older adults. *Psychology and Aging, 11*, 475-486.

Stine-Morrow, E. A. L., Miller, L. M. S., Gagne, D. D., & Hertzog, C. (2008). Self-regulated reading in adulthood. *Psychology and Aging*, *23*, 131-153.

Stine-Morrow, E. A. L., Shake, M. C., Miles, J. R., Lee, K. L., Gao, X., & McConkie, G. (2010). Pay now or pay later: Aging and the role of boundary salience in self-regulation of conceptual integration in sentence processing. *Psychology and Aging, 25*, 168-176.

Stites, M. C., Federmeier, K. D., & Stine-Morrow, E. A. L. (2013). Cross-age comparisons reveal multiple strategies for lexical ambiguity resolution during natural reading. *Journal of Experimental Psychology: Learning Memory and Cognition, 39,* 1823-1841.

Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision*, *11*:13, 1–82.

Taikh, A., Hargreaves, I. S., Yap, M., & Pexman, P. M. (2015). Semantic classification of pictures and words. *Quarterly Journal of Experimental Psychology, 68,* 1502-1518.

Teramoto, W., Tao, K., Sekiyama, K. & Mori, S. (2012). Reading performance in middle-aged adults with declines in accommodation. *Attention, Perception, & Psychophysics*, *74*, 1722-1731.

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception and Psychophysics, 10,* 375–378.

Tremblay, M., & Lecours, A. R. (1989). Aging and the word frequency effect: A lexical decision investigation. *Neuropsychologia, 27,* 1197-1203.

Tydgat, I., & Grainger, J. (2009). Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 480-498.

Underwood, N., & McConkie, G. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly, 20,* 153-162.

van den Broek, P., Lorch, R. E. J., Linderholm, T., & Gustafson, M. (2001). The effects of readers'goals on inference generation and memory for texts. *Memory and*

Cognition, 29, 1081–1087.

van den Broek, P., Risden, K., & Husebye-Hartmann, E. (1995). The role of reader's standards of coherence in the generation of inferences during reading. In E. P. Lorch & E. J. O'Brien (Eds.), *Sources of coherence in reading* (pp. 353–374). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc

Van Dyke, J. A., Johns, C. L, & Kukona, A. (2014). Low working memory capacity is only spuriously related to poor reading comprehension. *Cognition*, *131,* 373-403.

van Heuven, W. J. B, Manderab, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *The Quarterly Journal of Experimental Psychology*, *67*, 1176-1190.

Vasilev, M. R. & Angele, B. (2017). Parafoveal preview effects from word N + 1 and word N + 2 during reading: A critical review and Bayesian meta-analysis. *Psychonomic Bulletin & Review, 24,* 666-689.

Velan, H., & Frost, R. (2007). Cambridge University versus Hebrew University: The impact of letter transposition on reading English and Hebrew. *Psychonomic Bulletin & Review, 14*, 913-918.

Veldre, A., & Andrews, S. (2014). Lexical Quality and Eye Movements Individual Differences in the Perceptual Span of Skilled Adult Readers. *Quarterly Journal of Experimental Psychology, 67,* 703-727.

Venables, W. N., & Ripley, B. D. (2002). *Modern applied statistics with S (4th ed.)*. New York, USA: Springer.

Vitu, F., & McConkie, G. W. (2000). Regressive saccades and word perception in adult reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 301–326). BV, Netherlands: Elsevier.

Walker, R., Bryan, L., Harvey, H., Riazi, A., Anderson, S. J. (2016). The value of Tablets as reading aids for individuals with central visual field loss: An evaluation of eccentric reading with static and scrolling text. *Ophthalmic & Physiological Optics, 36,* 355-512.

Wandell B. (1995). *Foundations of Vision*. Massachusetts, USA: Sinauer Associates.

Wang, C. A., & Inhoff, A. W. (2010). The influence of visual contrast and case changes on parafoveal preview benefits during reading. *Quarterly Journal of Experimental Psychology, 63*, 805–817.

Wang, J., Li, L., Li, S., Xie, F., Chang, M., Paterson, K.B., White, S. J., & McGowan, V. A. (in press). Adult age differences in eye movements during reading: The evidence from Chinese. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences.*

Wheeler, D. D. (1970). Processes in word recognition. *Cognitive Psychology, 1,* 59-85.

White, S. J., Drieghe, D., Liversedge, S. P., & Staub, A. (2018). The word frequency effect during sentence reading: A linear or nonlinear effect of log frequency? *The Quarterly Journal of Experimental Psychology.*

White, S. J., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2008). Eye movements when reading transposed text: The importance of word beginning letters. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1261-1276.

White, S. J., Rayner, K., & Liversedge, S. P. (2005). The influence of parafoveal word length and contextual constraint on fixation durations and word skipping in reading. *Psychonomic Bulletin & Review, 12*, 466-471.

White, S. J., & Staub, A. (2012). The distribution of fixation durations during reading: Effects of visual quality. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 603-617.

White, S. J., Staub, A., Drieghe, D., & Liversedge, S. P. (2011). Word frequency effects during reading: Binocular fixations and the distribution of fixation durations. *European Conference on Eye Movements*, Marseille, France.

Whitford, V., & Titone, D. (2016). Eye movements and the perceptual span during first- and second-language sentence reading in bilingual older adults. *Psychology and Aging, 31*, 58-70.

Whitford, V., & Titone, D. (2017). The effects of word frequency and word predictability during first- and second-language paragraph reading in bilingual older and younger adults. *Psychology and Aging, 32,* 158-177.

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin &*

Review, 8, 221–243.

Williams, C. C., Perea, M., Pollatsek, A., & Rayner, K. (2006). Previewing the neighborhood: the role of orthographic neighbors as parafoveal previews in reading. *Journal of Experimental Psychology: Human Perception and Performance,* 32, 1072-1082.

Winskel, H., Ratitamkul, T., & Perea, M. (in press). Can the first letter advantage be shaped by script-specific characteristics? *Journal of Experimental Psychology: Learning, Memory, & Cognition***.**

Wlotko, E. W., Federmeier, K. D., & Kutas, M. (2012). To predict or not to predict: Age-related differences in the use of sentential context. *Psychology and Aging, 27,* 975-988.

Wonnacott, E., Joseph, H. S. S. L., Adelman, J. S. & Nation, K. (2016) Is children's reading "good enough"? Links between online processing and comprehension as children read syntactically ambiguous sentences. *Quarterly Journal of Experimental Psychology, 69*, 855-879.

Wotschack, C., & Kliegl, R. (2013). Reading Strategy Modulates Para-foveal-on-Foveal Effects in Sentence Reading. *Quarterly Journal of Experimental Psychology, 66,* 548-562.

Xing, J., & Heeger, D. J. (2000). Center-surround interactions in foveal and peripheral vision. *Vision Research, 40,* 3065–3072.

Yan, M., Richter, E., Shu, H., & Kliegl, R. (2009). Chinese readers extract semantic information from parafoveal words during reading. *Psychonomic Bulletin & Review, 16,* 561-566.

Yan, M., Zhou, W., Shu, H., & Kliegl, R. (2015). Perceptual span depends on font size during the reading of Chinese sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41,* 209-219.

Yang, S. N., & McConkie, G. W. (2001). Eye movements during reading: a theory of saccade initiation times. *Vision Research, 41,* 3567-3585.

Yang, S. N., & McConkie, G. W. (2004). Saccade generation during reading: Are words necessary? *European Journal of Cognitive Psychology, 16,* 226–261.

Yang, J., Wang, S., Tong, X., & Rayner, K. (2012). Semantic and plausibility effects on preview benefit during eye fixations in Chinese reading. *Reading and Writing, 25,* 1031-1052.

Yap, M. J., & Balota, D. A. (2007). Additive and interactive effects on response time distributions in visual word recognition. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 33,* 274-296.

Yap, M., & Balota, D. (2015). Visual Word Recognition. In A. Pollastsek & R. Treiman (Eds.), *The Oxford Handbook of Reading* (pp. 26-43). New York, NY: Oxford University Press.

Yap, M. J., Balota, D. A., Tse, C. S., Besner, D. (2008). On the additive effects of stimulus quality and word frequency in lexical decisions: Evidence for opposing additive influences revealed by RT distributional analyses. *Journal of Experimental Psychology: Learning, Memory & Cognition, 34,* 495-513.

Yap, M. J., Sibley, D. E., Balota, D. A., Ratcliff, R., & Rueckl, J. (2015) Responding to Nonwords in the Lexical Decision Task: Insight from the English Lexicon Project. *Journal of Experimental Psychology: Learning and Memory and Cognition. 41,* 597-613.

Zang, C., Zhang, M., Bai, X., Yan, G., Paterson, K. B., & Liversedge, S. P. (2016). Effects of word frequency and visual complexity on eye movements of young and older Chinese readers. *The Quarterly Journal of Experimental Psychology*, 69, 1409-1425.

Zhang, S., & Perfetti, C. A. (1993). The tongue-twister effect in reading Chinese. *Journal of experimental psychology: Learning, Memory, and Cognition*, *19,* 1082-1093.