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Aging and the Control of Binocular Fixations during Reading

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Abstract

Older adults (65+ years) often have greater difficulty in reading than young adults (18-30 years). However, the extent to which this difficulty is attributable to impaired eye-movement control is uncertain. To address this issue, the alignment and location of the two eyes' fixations during reading were monitored for young and older adults. Older adults showed typical patterns of reading difficulty but the results revealed no age differences in the alignment or location of the two eyes' fixations. Thus, the difficulty older adults experience in reading is not related to oculomotor control, which appears to be preserved into older age.

Key Words: Aging; Eye Movements; Reading

When reading, the eyes move along each line of text in a sequence of saccadic movements separated by brief fixational pauses during which visual information is acquired from the page. Throughout each saccade, the two eyes move in the same direction and with roughly the same speed, although small differences in velocity can cause brief periods of disconjugacy (e.g., Collewijn, Erkelens, & Steinman, 1988a, 1988b; Fioravanti, Inchingolo, Pensiero, & Spanio, 1995), during which the rotation of the eyes, and therefore the direction of each eye's gaze, differs. It nevertheless has long been assumed that after each saccade, the resulting fixations of each eye are closely aligned so that efficient reading can take place.

However, recent research shows that the locations fixated by the two eyes often differ substantially during each fixational pause (e.g., Kliegl, Nuthmann, & Engbert, 2006; Liversedge, White, Findlay, & Rayner, 2006; Paterson, Jordan, & Kurtev, 2009; see also Kirkby, Webster, Blythe, & Liversedge, 2008). In particular, the two eyes typically fail to fixate the same character within a word on about 50% of fixational pauses, and misaligned fixations can be as much as two or more characters apart and may even be on different words. Moreover, misaligned fixations can be either crossed (when the right eye fixates to the left of the left eye's fixation), or uncrossed (when the right eye fixates to the right of the left eye's fixation), and the nature and extent of disparity may vary across fixational pauses.

Fixation disparity is likely to be an important component of reading difficulty (e.g., Blythe, Liversedge, Joseph, White, Findlay, & Rayner, 2006; Kirkby, Blythe, Drieghe, & Liversedge, 2011) and appears to change as children mature into young adulthood (e.g., Fioravanti et al., 1995; Yang & Kapoula, 2003). For instance, the fixations of beginning readers (under 10 years of age) and child readers with developmental dyslexia are more likely to be misaligned, and to have greater disparity, than those of young (non-dyslexic) adult readers (e.g., Blythe et al., 2006; Kirkby et al., 2011). But major changes in the visual system continue into later adulthood through normal aging (e.g., Kerber, Ishiyama, & Baloh, 2005;

for a review, see Owsley, 2011), and these changes appear to include a general increase in both the frequency and size of fixation disparities as adults reach older age, shown by ophthalmological assessments using non-reading tasks (e.g., Yekta, Pickwell, & Jenkins, 1989; see also Zaroff, Knutelska, & Frumkes, 2003). In addition, studies using various other non-reading tasks (e.g., visual search, anti-saccade tasks) show that in general accuracy of saccadic eye movements increases from childhood into early adulthood but eye movements are slower and less accurate for older adults than for young adults (e.g., Irving, Steinbach, Lillakas, Babu,& Hutchings, 2006; Nieuwenhuis, Ridderinkhof, de Jong, Kok, & van der Molen, 2000; Peltsch, Hemraj, Garcia, & Munoz, 2011; Pratt & Chasteen, 1998; Warabi, Kase, & Kato, 2004).

Older adults also typically read more slowly, make more and longer eye fixations, longer progressive saccades (forward eye movements), and more regressions (backwards eye movements) than young readers (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Castelhano, & Yang, 2009; see also Laubrock, Kliegl, & Engbert, 2006; Paterson, McGowan, & Jordan, 2013). This age-related change in eye movement behavior is often attributed to older adults adopting a different reading strategy to compensate for their poorer processing of text (e.g., Rayner et al., 2006, 2009). But the extent to which it is due to impaired eye movement control is unknown. Consequently, while eye guidance and fixation disparity may improve with maturation into young adulthood, poor saccadic control and increased fixation disparity may re-emerge in later life and be an important component of the difficulty experienced by older readers.

A particularly crucial aspect of the reading process that may be especially susceptible to impaired eye movement control in later life is the targeting of saccades towards particular locations in words. Indeed, readers generally fixate a *preferred viewing location* (PVL; e.g., McConkie, Kerr, Reddix, & Zola, 1988; Plummer & Rayner, 2012; Rayner, 1979) which is typically a little to the left of the center of words. However, if the frequency or size of fixation disparity during reading increases with older age, the probability of both eyes fixating the PVL will be reduced and produce different patterns of fixation location compared to younger adults. Moreover, poor eye guidance may cause older readers to overshoot or undershoot the PVL, and this may impair reading performance. Previous experimental investigations of the PVL recorded only monocular eye movements (usually from the right eye), but findings from a recent corpus analysis of binocular eye movements suggest that fixation disparity during reading produces qualitatively different PVLs for each eye (Nuthmann & Kleigl, 2009). However, neither this nor any other study has examined adult age differences in these PVLs, and so it remains to be determined if increases in either the frequency or size of fixation disparity with older age contribute to different patterns of PVLs.

Accordingly, we assessed the binocular eye movements of young (18-30 years) and older (65-74 years) adults as they read lines of text. If older age impairs the ability to coordinate binocular fixations when reading, older adults should produce more misaligned fixations and larger disparity in the locations of the two eyes' fixations compared to younger adults. In addition, if age-related increases in the frequency or size of this misalignment affect the locations fixated in words, or if normal aging impairs eye guidance, young and older adults should produce different PVLs. Consequently, we assessed effects of age on PVLs closely by including in each sentence a specific target word of either 4 or 10 letters, matched for lexical frequency.

Method

Participants. Thirty-two adults participated in the experiment; 16 young adults (average age = 22 years, range = 19-30 years) and 16 older adults (average age = 69 years, range = 65-74 years). All were native English speakers and were screened for right and left monocular visual acuity and binocular visual acuity using an ETDRS letter chart (Ferris &

Bailey, 1996), and for contrast-sensitivity using the Hamilton-Veale test. Screening showed that participants did not suffer from eye disease or disorders (e.g., amblyopia), or visual or reading impairment (e.g., dyslexia). Older adults showed lower visual acuity than young adults (older adults, *M* = 20/25, range = 20/17 to 20/33, young adults, *M* = 20/18, range = 20/13 to 20/26, where acuity is reported in Snellen values) and lower log contrast sensitivity (older adults, *M* = 1.79, range = 1.65 – 1.80, young adults, *M* = 1.82, range = 1.80 – 1.95). Both age groups had similar educational backgrounds (older adults, *M* = 17 years, range = 11-25 years, young adults, *M* = 17 years, range = 14-24 years) and reported similar reading experience (older adults, *M* = 17.0 hours/week, range = 2 - 50 hours/week, young adults, *M* = 19.3 hours/week, range = 1 - 45 hours/week).

Stimuli and Design. Forty sentence frames were used and each was completed plausibly by each of a matched pair of target words presented at the same location near the middle of each sentence. Target words were 40 pairs of short (4-letter) and long (10-letter) words matched for lexical frequency using the CELEX database (mean 48.5 counts / million for short words and 36.7 counts / million for long words; Baayen, Piepenbrock, & Gulikers, 1995; e.g., "He poured a very big coffee for the company boss / specialist as he wanted a pay rise." where the alternative target words are shown separated by a forward slash). As the sentence frames were identical for each member of a target word pair, the part of the sentence that preceded the target word was always identical. Complete sentences were between 71 and 80 characters long (mean = 76 characters), and contained between 11 and 16 words (mean = 14 words). Each participant saw each combination of sentence frame and target word once, and so saw a total of 80 stimuli. Each sentence was followed by a comprehension question (e.g., "Was the coffee small?"). These stimuli were shown across two sessions with each sentence frame shown once per session, each target word selected randomly and shown once per session, and each session counterbalanced for target word length. In each session, the 40 experimental items were shown in a randomized order.

Apparatus. A desktop mounted SR Research Eyelink 2000 eye-tracker recorded binocular gaze location each millisecond. Stimuli were presented as black text on a white background in Courier font on a 19 inch monitor. Each sentence started at the same location in the center left of the screen. Each character space subtended approximately .25°, and so text was presented at a size that was normal for reading (e.g., Rayner & Pollatsek, 1989).

Procedure. Participants were instructed to read normally and for comprehension. At the start of the experiment, a 3-point calibration procedure was conducted monocularly for each eye. A central drift check was conducted binocularly prior to each trial and a 3-point drift check covering the same area was conducted monocularly for each eye after every three trials. At the start of each trial, a fixation square equal in size to a character space was presented to the left of the screen. Once this was fixated, a sentence was presented with its first letter replacing the square. Participants pressed a response key when they finished reading each sentence. The sentence was then replaced by a comprehension question, to which participants responded.

Results

Sentence-Level Analyses

Table 1a shows comprehension accuracy and eye movement measures (Rayner, 2009) for both age groups. These measures were computed monocularly for the right eye to ensure comparability with previous research.[1] Comprehension accuracy was high for young and older adults and did not differ between age groups ($t<1$). Average fixation duration also did not differ between age groups ($t<1$), but older adults had longer reading times, $t(30) = 2.05$, $p<.05$, made more fixations, $t(30) = 2.13$, $p<.05$, longer progressive saccades, $t(30) = 3.77$, $p<.01$, and more regressions, $t(30) = 3.56$, $p<.01$, than young adults. These findings therefore closely resembled those from previous research (Kliegl et al., 2004; Rayner et al., 2006).

----------------------Table 1----------------------

Fixation Alignment & Disparity. Binocular fixations were considered aligned if the point of gaze of each eye fell within the width of one character space (see Liversedge, White, et al., 2006). Misaligned fixations were *crossed* when the right eye fixated more than one character space to the left of the left eye's fixation, and *uncrossed* when the right eye fixated more than one character space to the right of the left eye's fixation. Alignment was assessed at the beginning and end of each fixational pause. Disparity in the location of the two eyes' fixations was calculated in character spaces, and computed separately for all fixations and for only those fixations that were misaligned.

Young and older adults showed similar numbers of aligned fixations at both the beginning and end of each fixational pause (see Table 1b). For both age groups, the vast majority of misaligned fixations were crossed rather than uncrossed. An Analysis of Variance (ANOVA) with factors age (young, older), fixation type (aligned, crossed, uncrossed) and time of occurrence in fixational pause (beginning, end) showed no influence of age on the proportion of each fixation type at either the beginning or end of each fixational pause (Fs <1.7). Additional analyses showed that age also did not affect the extent of the disparity at the beginning or the end of fixational pauses, either when the analysis included all fixations (young adults, mean = 1.2 characters, SE = .2; older adults, mean = 1.4 characters, SE = .2; ts <1.2), or only misaligned fixations (young adults, mean = 1.9 characters, SE = .1; older adults, mean = 2.0 characters, SE = .1; ts <1.3). Thus, there was no indication that the frequency or size of fixation disparity was greater for older adults than for young adults.

Target Word Analyses.

Table 2a shows monocular eye movement measures, computed from the right eye, for target words (e.g., Rayner, 2009) for both age groups. Data for each measure were subjected to an ANOVA with factors age and word length (short, long). Effects of age showed that older adults had longer total reading times, $F(1,30)=5.21$, $p<.05$, $\eta_p^2= .15$, made more fixations, $F(1,30)=4.85$, $p<.05$, $\eta_p^2= .14$, and more regressions back to the target words, $F(1,30)=10.10$, $p<.01$, $\eta_p^2= .25$, than young adults, but no effects of age were observed for first fixation durations, gaze durations, number of first-pass fixations (*F*s<1), or for word-skipping rates, $F(1,30)=2.93$, $p=.10$, $\eta_p^2= .09$. In addition, short words received shorter gaze durations, $F(1,30)=19.57$, $p<.001$, $\eta_p^2= .40$, fewer first-pass fixations, $F(1,30)=35.10$, $p<.001$, $\eta_p^2= .54$, shorter total reading times, $F(1,30)=64.94$, $p<.001$, $\eta_p^2= .68$, fewer fixations overall, $F(1,30)=98.96$, $p<.001$, $\eta_p^2= .77$, and fewer regressions, $F(1,30)=5.37$, $p<.05$, $\eta_p^2= .15$, compared to long words, and short words were more likely to be skipped, $F(1,30)=52.62$, $p<.001$, $\eta_p^2= .64$, than long words. No effects of word length were observed for first fixation durations or regressions (*F*s<1), and there were no interactions of age and word length (*F*s<2.5). Thus, the effects observed for word length were similar for young and older adults.

-----------------------Table 2-----------------------

Fixation Alignment & Disparity. An ANOVA with factors age, word length, and fixation type showed that the number of fixations of each type was unaffected by age or word length (*F*s<1.3; see Table 2b). In addition, no effect of age or word length were observed on the size of the disparity, either when this was computed for all fixations or only misaligned fixations (*F*s<1.5).

Initial Landing Positions. Initial landing positions for each eye are shown in Figure 1. ANOVAs with factors age, word length, and eye (right, left) showed no effects of age (*F*s<1.4), and landing positions for the left eye did not differ from those for the right eye ($F<1$). For both eyes, initial landing positions were further in from the left boundary of short words than of long (63% vs.41% from the left word boundary), $F(1,30)=267.73$, $p<.001$, $\eta_p^2= .90$. No other effects were significant (*F*s<1.5). Thus, although word length affected initial landing position, this effect was similar for right and left eye fixations and unaffected by age.

----------------------Figure 1----------------------

Discussion

The findings of this study show older adults read more slowly than young adults, and also made more fixations, longer progressive saccades, and more regressions, and for target words had longer reading times, made more fixations, and more regressions. This pattern is generally consistent with findings from previous studies comparing the reading performance of young and older adults, suggesting that readers in the present study performed in a typical fashion (e.g., Kliegl et al., 2004; Rayner et al., 2006, 2009; see also Laubrock et al., 2006). This pattern of findings is often interpreted as showing older adults have greater difficulty in reading and, in particular, that older readers adopt a “riskier” reading strategy in which they compensate for their poorer processing of text by attempting to decide the identities of words on the basis of partial word information more often than young adults (e.g., Rayner et al., 2006, 2009).

However, the present research shows that the difficulty older readers experience is not associated with increased frequency or size of fixation disparity, or impaired targeting of fixations in words. More specifically, although approximately half of all fixations were misaligned, the proportions of each type of fixation and the degree of disparity that occurred did not differ between young and older adults. These proportions for the fixations of young and older adults agree with those reported previously for only young adults (e.g., Liversedge, White, et al., 2006; Kleigl et al., 2006), and the prevalence of crossed over uncrossed fixations is also consistent with previous studies of young adults that used the same eye-tracker and similar experimental procedures (e.g., Kleigl et al., 2006). Moreover, the present research also revealed very little difference in the PVLs produced by young and older adults, for either short or long target words. These PVLs were also similar to those obtained for young adults in previous research and tended to undershoot the center of long words and overshoot the center of short words (e.g., Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie et al., 1988). In addition, and as in previous research with young and older adults, the two age groups were equally more likely to skip short than long words (Kleigl et al., 2004). The indications are, therefore, that young and older readers make similar use of parafoveal information about word length to direct fixations towards words (e.g., Plummer & Rayner, 2012; for a review, see Schotter, Angele, & Rayner, 2012). Finally, as PVLs produced by right and left eye fixations differed little from each other or for young compared to older adults, it appears that right and left eyes were directed towards similar locations in words, and age did not affect the location or accuracy of these fixations. Thus, the findings of this study integrate closely with previous research to provide coherent and comprehensive indications that oculomotor control during reading does not change as adults reach older age. It seems likely these findings will also be enlightening for understanding oculomotor control by young and older adults with visual or reading impairments, and the processing of text in less-than-ideal viewing conditions.

Since changes in oculomotor control are not implicated in the poorer reading performance shown by older adults in the present research, it seems likely that this poorer performance reflects changes in other aspects of reading. For example, older adults have specific difficulty processing words and the syntactic and discourse levels of analysis during reading, and these differences may reflect more general age-related changes in working memory and attention (e.g., Kemper et al., 2004; Rayner et al., 2006; Stine-Morrow, Soederberg Miller, & Hertzog, 2006), or the use of strategies that compensate for these losses to maintain good comprehension. Poorer reading performance by older adults may also be inspired by substantial changes in vision that occur as a result of normal aging, including loss of high-contrast near-vision acuity and reductions in spatial frequency sensitivity (see, e.g., Derefelt, Lennerstrand, & Lundh, 1979; Elliott, Yang, & Whitaker, 1995; Owsley, Sekuler, Siemsen, 1983; for a review, see Owsley, 2011). Indeed, the older participants in our study showed evidence of these changes. But other research shows that a wide range of spatial frequencies may be used for reading, by young and older adults (e.g., Jordan, McGowan, & Paterson, 2012; Legge, Pelli, Rubin, & Schleske, 1985; Paterson, McGowan, & Jordan, 2012a, 2012b). Consequently, precisely how reductions in acuity and contrast-sensitivity observed for older readers in the present research, and prevalent for older adults in the general population (e.g., Derefelt et al., 2005; Laitinen, Koskinen, Härkänen, Reunanen, Laatikainen, & Aromaa, 2005), affect reading performance remains to be fully determined. Nevertheless, it seems likely that changes in visual sensitivity contribute substantially to the difficulties in reading that are experienced by older adults (e.g., Laubrock et al., 2006; Paterson et al., 2012a; Rayner et al., 2009).

However, it is clear from the present research that age-related changes in vision do not affect eye guidance during reading, and this may reflect the nature of the visual changes that occur as adults reach older age. In particular, although healthy aging shows a general decline in visual sensitivity, this decline occurs primarily for higher spatial frequencies (e.g., Crassini, Brown, & Bowman, 1988; Derefelt et al., 1979; Owsley et al., 1983). Consequently, changes in visual sensitivity as adults reach older age may not affect the targeting of fixations during reading because effective eye guidance requires only relatively coarse-scale visual cues to the location and length of words (e.g., Jordan, 1990, 1995; Jordan, Thomas, Patching, & Scott-Brown, 2003; Pollatsek & Rayner, 1982). This process may also be helped by the nature of reading, which is a highly practiced visual task involving sequences of relatively short saccades to predictable targets in a familiar and consistent spatial format.

The constancy of eye guidance in reading across young and older adults contrasts with findings in other domains showing that saccadic eye movements are often slower and less accurate for older adults than for young adults (for a review see e.g., Peltsch et al., 2011). Older adults also show increases in the frequency and size of fixation disparity compared to young adults in ophthalmological assessments (e.g., Yekta et al., 1989; see also Zaroff et al., 2003). However, the disparities observed in these assessments are typically similar in size (.25° or less on the vast majority of tests) to those observed for both young and older adults in the present study and, as in the present study, misaligned fixations are more often crossed than uncrossed. Consequently, while differences in eye-guidance between young and older adults can be observed in other tasks, young adults may be able to align their fixations more precisely than older adults in overt fixational procedures whereas the automaticity of reading (e.g., Rayner, 2009) may make it a special case for eye guidance in which the frequency and size of fixation disparity is resilient to effects of older age.

The present findings also show an important distinction between effects of adult aging on reading and previous findings showing that an increase in the frequency and size of fixation disparity is associated with reading difficulty (e.g., Blythe et al., 2006; Kirkby et al., 2011). These previous studies were concerned with the eye movement performance of beginning readers (under 10 years) and child readers with developmental dyslexia. Therefore, the difficulties experienced by these readers and the role of fixation disparities in their reading performance are likely to be different from those of skilled older readers. Moreover, the increased frequency and size of the fixation disparity observed in these previous studies is likely to reflect the relative immaturity of the visual systems of beginning readers (e.g., Fioravanti et al., 1995; Yang & Kapoula, 2003), and even impairments to the visual systems of dyslexic readers (e.g., Stein, 2001). Consequently, eye movement control in reading may be unimpaired as young adults reach older age because of the maturity of their visual systems and their greater expertise and experience of reading.

Finally, old and young readers in the present research produced similarly high levels of performance on tests of reading comprehension. The indications from the findings of this study, therefore, are that although aging leads to important changes in reading, not only is the eye movement control shown by young adult readers preserved in older age, but older readers continue to achieve good comprehension. Indeed, the high level of comprehension achieved by older adults in the present research suggest that, despite reading more slowly than young adults, older adults employ a reading strategy that is well-adapted to the task and that helps them continue to read effectively well into later life.

Footnote

1. Differences between monocular fixation counts in Tables 1a and 2a and binocular fixation counts in Tables 1b and 2b reflect a small number of fixations in which fixation data were unavailable for both eyes and so binocular coordination could not be computed.

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Table 1

a: Comprehension Accuracy and Sentence-Level Eye Movement Measures*

Age	Comprehension Accuracy (%)	Reading Time (ms)	Average Fixation Duration (ms)	Number of Fixations	Progressive Saccade Amplitude (characters)	Number of Regressions
Young Adults	94.1	3718	218	14.5	8.4	3.4
	(.6)	(155)	(6)	(.6)	(.3)	(.3)
Older Adults	94.4	4408	219	17.2	13.0	5.6
	(.7)	(300)	(6)	(1.1)	(1.2)	(.5)

b: Mean Number of Aligned, Crossed, and Uncrossed Fixations For Sentences*

	Fixation Alignment		
	Aligned	Crossed	Uncrossed
Beginning of Fixation			
Young Adults	7.2 (0.9)	4.9 (1.0)	1.0 (0.2)
Older Adults	6.9 (0.7)	6.5 (1.2)	2.2 (0.5)
End of Fixation			
Young Adults	8.1 (0.9)	4.4 (0.9)	0.6 (0.2)
Older Adults	8.3 (1.1)	6.2 (1.0)	1.0 (0.4)

* Standard Errors are provided in parentheses.

Table 2

a: Eye Movement Measures for Target Words*

Measure	Young Adults		Older Adults	
	Word Length			
	Short	Long	Short	Long
First Fixation Duration (ms)	237 (9)	232 (8)	228 (7)	227 (7)
Gaze Duration (ms)	253 (9)	291 (14)	250 (9)	268 (11)
Total Reading Time (ms)	322 (11)	423 (23)	392 (26)	508 (37)
First-Pass Fixations	1.1 (.01)	1.3 (.04)	1.1 (.02)	1.2 (.04)
Total Fixation Count	1.2 (.05)	1.9 (.09)	1.6 (.12)	2.2 (.17)
Regressions In (%)	20.9 (2.5)	28.0 (3.5)	36.1 (2.4)	37.7 (3.5)
Word-Skipping (%)	20.5 (3.5)	2.5 (1.1)	26.9 (4.1)	8.0 (2.4)

b: Mean Number of Aligned, Crossed, and Uncrossed Fixations, and Mean Fixation Disparity (in Characters) for All Fixations and Only Unaligned Fixations for Target Words*

		Fixation Alignment			Fixation Disparity	
	Word Length	Aligned	Crossed	Uncrossed	All Fixations	Unaligned Fixations
Young Adults	Short	0.7 (0.1)	0.4 (0.1)	0.1 (0.0)	1.1 (0.2)	1.8 (0.1)
	Long	1.0 (0.1)	0.7 (0.1)	0.1 (0.0)	1.1 (0.2)	1.8 (0.1)
Older Adults	Short	0.7 (0.1)	0.6 (0.1)	0.1 (0.0)	1.3 (0.1)	2.0 (0.1)
	Long	1.0 (0.1)	0.9 (0.2)	0.2 (0.1)	1.4 (0.2)	2.0 (0.2)

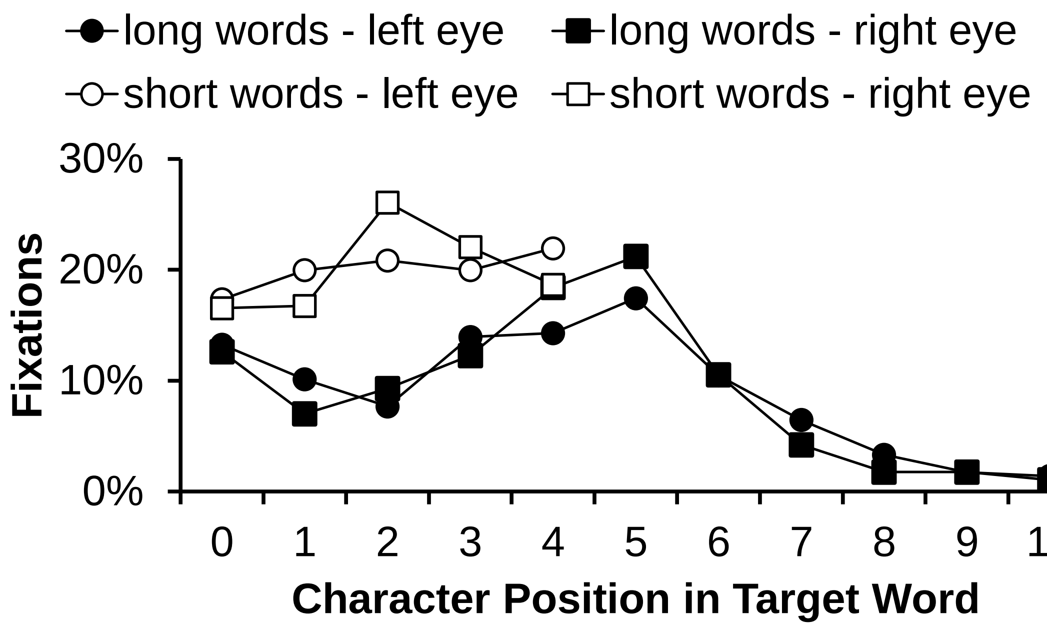
* Standard Errors are provided in parentheses.

Legend

Figure 1. Locations of Initial Landing Positions for Left and Right Eyes in Short and Long Words for Young and Older Adults.

Figure 1

Young Adults



Older Adults