Psychon Bull Rev (2014) 21:740–747
DOI 10.3758/s13423-013-0527-8

BRIEF REPORT

Aging and the use of interword spaces during reading: Evidence from eye movements

Victoria A. McGowan · Sarah J. White · Timothy R. Jordan · Kevin B. Paterson

Published online: 8 October 2013

Abstract In an eye movement experiment, we assessed the performance of young (18–30 years) and older (65 + years) adult readers when sentences contained conventional interword spaces, when interword spaces were removed, or when interword spaces were replaced by nonlinguistic symbols. The replacement symbol was either a closed square (■) that provided a salient (low-spatial-frequency) cue to word boundaries, or an open square (□) that provided a less salient cue and included features (vertical and horizontal lines) similar to those found in letters. Removing or replacing interword spaces slowed reading times and impaired normal eye movement behavior for both age groups. However, this disruption was greater for the older readers, particularly when the replacement symbol did not provide a salient cue as to word boundaries. Specific influences of this manipulation on word identification during reading were assessed by examining eye movements for a high- or low-frequency target word in each sentence. Standard word frequency effects were obtained for both age groups when text was spaced normally, and although the word frequency effect was larger when spaces were removed or filled, the increases were similar across age groups. Therefore, whereas older adults' normal eye movements were substantially disrupted when text lacked conventional interword spaces, the process of lexical access associated with the word frequency effect was no more difficult for older than for young adults. The indication, therefore, is that although older adults struggle from the loss of conventional cues to word boundaries, this is not due to additional difficulties in word recognition.

Keywords Eye movements · Reading · Older adults

V. A. McGowan (✉) · S. J. White · T. R. Jordan · K. B. Paterson
School of Psychology, University of Leicester, Lancaster Road, Leicester LE1 9HN, UK
e-mail: Vam12@le.ac.uk

A wealth of evidence demonstrates adult age differences in eye movements while reading. In particular, older adult readers (65 + years) typically make more and longer eye fixations, longer progressive saccades (forward movements in text), more regressions (backward movements in text), skip words more often, and have longer reading times than young adult readers (18–30 years; e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Castelhano, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; see also Paterson, McGowan, & Jordan, 2013a, 2013b, 2013c). Moreover, whereas older readers show word frequency effects in which, like younger readers, they fixate longer on words that typically are encountered less frequently in text (Rayner et al., 2006), these effects may be larger for older readers.

This age-related difference in eye movement behavior is widely attributed to older adults adopting a "riskier" reading strategy to compensate for their poorer processing of text than do young adults (e.g., Rayner et al., 2006). Indeed, substantial changes in visual abilities occur with normal aging, and older adults often experience a range of subtle visual deficits that may affect the visual processing of text (for a recent review, see Owsley, 2011). This manifests predominantly as a progressive decline in sensitivity for fine visual detail, and is widely attributed to a combination of optical changes and changes in neural transmission as adults reach older age (e.g., Crassini, Brown, & Bowman, 1988; Elliott, Yang, & Whitaker, 1995; Owsley, Sekuler, & Siemsen, 1983). These changes in visual abilities may also relate to increased effects of visual crowding on the perceptual abilities of older adults (McCarley, Yamani, Kramer, & Mounts, 2012; Scialfa, Cordazzo, Bubric, & Lyon, 2013), characterized by the reduced ability to recognize visual objects in clutter (Bouma, 1971; see also Pelli & Tillman, 2008). However, the precise effects of these changes on the reading ability of older adults have yet to be established.

Of particular concern for the present research is the role of the spaces between words in text. Text in most alphabetic languages customarily includes spaces between words. By helping to demarcate word boundaries, these may aid the processing of words by reducing visual crowding and lateral masking (interference from flanking letters) of exterior letters in words (e.g., Bouma, 1971). Moreover, interword spaces convey valuable coarse-scale (i.e., low spatial-frequency) information about the location and physical extent of words, by segregating text into bands of light and dark, which may provide a useful clue to the identity of words in parafoveal and peripheral vision and be important for planning saccadic eye movements (e.g., Perea & Acha, 2009; Pollatsek & Rayner, 1982).

Indeed, it is well-established that removing or replacing the spaces between words (in languages that customarily include spaces) disrupts normal reading (e.g., Malt & Seamon, 1978; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Rayner, Yang, Schuett, & Slattery, 2013; Sheridan, Rayner, & Reingold, 2013). Particularly clear evidence for this has come from studies in which participants read spaced and unspaced text that included one of a pair of target words that differed in frequency of usage (e.g., Rayner et al., 1998; Rayner et al., 2013): Unspaced text increased the size of the word frequency effect obtained for spaced text by making lower-frequency words disproportionately harder to identify. This showed that removing interword spaces directly influenced the process of word identification during reading rather than only a more superficial level of visual processing. Typically less disruption is observed when interword spaces are replaced with other delimiters, especially nonlinguistic symbols (e.g., shaded boxes) that provide coarse-scale cues to word boundaries (e.g., Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Pollatsek & Rayner, 1982). In addition, delimiters with visual features dissimilar to those found in letters produce less crowding (e.g., Bouma, 1971), and so may provide more effective cues to word boundaries. Consequently, the indication is that readers can adapt to the loss of conventional interword spaces, especially when alternative coarse-scale cues are available.

Much of this prior research was concerned with the performance of young adult readers, and thus it is pertinent to investigate whether the visual changes that occur with more advanced age may lead to greater difficulties with unspaced and filled-space text. Indeed, a recent study (Rayner et al., 2013) showed that older adults experienced greater difficulties in reading unspaced text than did young adults, although a word frequency manipulation indicated that this was not due to additional difficulties in word recognition.

The present research expands upon the findings of Rayner et al. (2013) by examining the effectiveness of novel visual cues as to word boundaries. In addition to examining eye movements for spaced and unspaced text, young and older adults read text in which the spaces between words were replaced with either open (□) or closed (■) squares (see Fig. 1). These replacement symbols enabled us to compare whether young and older readers are able to use nonlinguistic visual cues to segment words equally effectively. Furthermore, these two conditions allowed us to more closely examine which aspects of interword spacing are particularly valuable for older readers. Whereas closed squares provide a particularly salient (low-spatial-frequency) cue to word boundaries, open squares provide a less salient cue and include features (vertical and horizontal lines) similar to those found in letters, which may contribute to crowding. Consequently, differences in eye movement behavior for these replacement space conditions between the two age groups may indicate that young and older readers utilize interword spaces in different ways.

Following earlier research, we assessed the influence of this manipulation on sentence-level measures of eye movement behavior and eye movements for high- or low-frequency target words in each sentence (Rayner et al. 1998; Rayner et al., 2013). As in Rayner et al. (2013), if older adults suffered more than young adults from the loss of conventional interword spaces, normal reading times should be lengthened and normal eye movement behavior impaired more for older than for young adults when interword spaces are removed or replaced. Moreover, if the loss of these spaces impaired the normal process of word identification, this would enlarge the word frequency effect obtained for target words (by making lower-frequency words disproportionately harder to identify). Age differences in the size of this effect would also reveal whether older adults experience more difficulty than young adults in identifying words, either when text is spaced normally or when interword spaces are removed or replaced.

Method

Participants

The participants were 16 young adults (M = 19 years, range = 18–21 years) and 16 older adults (M = 72 years, range = 65–81 years) from the University of Leicester and the community.

Text Spaced Normally
`Take your money out of the account and pay the debt.`

Unspaced
`Takeyourmoneyoutoftheaccountandpaythedebt.`

Open Squares
`Take□your□money□out□of□the□account□and□pay□the□debt.`

Closed Squares
`Take■your■money■out■of■the■account■and■pay■the■debt.`

Fig. 1 An example sentence in each display condition

All were native English speakers and were screened for acuity at the viewing distance used in the experiment by using an EDTRS chart (Ferris & Bailey, 1996), and for contrast sensitivity using a Pelli–Robson chart (Pelli, Robson, & Wilkins, 1988). The two groups had similar educational backgrounds (young adults, M = 14.3 years, range = 12–17 years; older adults, M = 15.4 years, range = 10–21 years, ts < 1.5) and reported similar reading experience (young adults, M = 11.4 h/week, range = 4–22 h/week; older adults, M = 15.2 h/week, range = 5–35 h/week, ts < 1.5). As compared with the young adults, the older adults showed typical lower acuity [young adults, M = 20/17; older adults, M = 20/30; $t(30) = 5.61, p < .001$] and contrast sensitivity [young adults, M = 1.95; older adults, M = 1.90; $t(30) = 1.78, p < .09$].

Materials and design

The stimuli consisted of 80 sentence frames with an interchangeable high- or low-frequency target word (see Juhasz, Liversedge, White, & Rayner, 2006, for details). Each participant was presented with each target word and each sentence frame once. These sentences were shown in one of four display conditions (see Fig. 1): normal interword spacing, unspaced (in which interword spaces were removed), or interword spaces replaced with either open squares (□) or closed squares (■). A Latin square design ensured that each participant saw each target word and each sentence once in one of the display conditions, and that each participant group saw each target word and each sentence equal numbers of times in each display condition. Sentences were shown in one session to each participant, preceded by eight practice items (two per display condition).

Apparatus

An EyeLink 1000 eyetracker recorded gaze location every millisecond. Viewing was binocular, but only right eye movements were recorded. Stimuli were presented as black text on a white background in Courier font, and approximately 3.3 characters subtended 1 deg of visual angle.

Procedure

Participants were instructed to read normally and for comprehension. At the start of the experiment, a three-point horizontal calibration procedure was conducted, and calibration accuracy was checked before the presentation of each trial. 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 once they finished reading each sentence. The sentence was replaced by a comprehension question on 25 % of trials.

Results

Comprehension accuracy was high (above 90 %) for all participants and did not differ across display conditions or between young and older adults (all Ms > 95 %). A range of sentence-level measures were computed. These were sentence reading times, average fixation durations (average length of fixational pauses during reading), number of fixations, number of regressions (number of backward eye movements), and progressive saccade amplitude (the average length, in characters, of forward eye movements, which included the distance between words for the normal-space and filled-space conditions). In addition, a range of word-level measures were computed for high- and low-frequency target words in each sentence. These were first-fixation duration (the duration of the first fixation on a target word), gaze duration (the sum of all first-pass fixation durations on a target), total reading time (the sum of all fixation durations on a target), probability of making a regression back to the target word (often called "regressions in"), and probability of skipping a target word during the first pass (the word-skipping rate).

Following standard procedures, fixations shorter than 80 ms or longer than 1,200 ms were removed (affecting 2.7 % of fixations). For the word-level measures, trials were excluded if a blink preceded or followed a fixation on the target word (accounting for a further 2.9 % of trials for young adults and 13.1 % of trials for older adults), although the same pattern of findings was obtained in analyses that included blinks. The remaining data were analyzed using analyses of variance (ANOVAs) with the factors Age Group (young, older) and Display Condition (normal, unspaced, open squares, closed squares) for the sentence-level analyses, and including Frequency (high, low) as an additional factor for the word-level analyses. Variance was computed across participants (F_1) and items (F_2), and the Greenhouse–Geisser correction was used where appropriate. For all analyses, the design was mixed for the F_1 analyses and within items for the F_2 analyses. Pairwise comparisons were performed using Tukey tests ($p < .05$ for significant effects).

Sentence-level measures

Table 1 shows means for the sentence-level measures, and Table 2 reports the ANOVA statistics. Older adults showed longer reading times, more and longer fixations, more regressions, and longer progressive saccades than did young adults. These findings closely resemble those from previous research (Kliegl et al., 2004; Rayner et al., 2006; Rayner et al., 2013). Significant main effects of age group and display condition were qualified by interactions of these factors for all measures. For the young adults, spaced text produced the shortest reading times, fewest and shortest fixations, and longest progressive saccades, followed by closed squares, and then open

Table 1 Mean sentence-level measures for young and older adults in each display condition

Measure		Normal	Unspaced	Open Squares	Closed Squares
Reading time (ms)	Young adults	2,308 (163)	4,151 (336)	3,351 (183)	2,772 (184)
	Older adults	2,831 (238)	5,416 (432)	6,756 (444)	4,372 (269)
	AE	523	1,265	3,406	1,600
Fixation duration (ms)	Young adults	220 (4)	265 (5)	245 (5)	229 (4)
	Older adults	228 (5)	288 (8)	296 (8)	268 (7)
	AE	8	23	51	39
Number of fixations	Young adults	9.6 (0.7)	14.7 (1.1)	12.9 (0.8)	11.2 (0.8)
	Older adults	11.1 (0.9)	17.0 (1.3)	20.8 (1.4)	14.8 (0.8)
	AE	1.5	2.3	7.9	3.5
Number of regressions	Young adults	1.5 (0.2)	2.8 (0.4)	1.7 (0.2)	1.6 (0.3)
	Older adults	2.9 (0.3)	4.7 (0.6)	5.9 (0.6)	3.7 (0.3)
	AE	1.4	1.9	4.2	2.1
Progressive saccade length (characters)	Young adults	8.0 (0.3)	5.7 (0.3)	6.3 (0.3)	6.9 (0.2)
	Older adults	10.2 (0.7)	7.0 (0.5)	6.9 (0.5)	7.8 (0.5)
	AE	2.2	1.3	0.6	0.9

Standard errors are shown in parentheses. AE = age effect

squares, and unspaced text produced the longest reading times, longest and most fixations, most regressions, and shortest progressive saccades. For the older adults, spaced text produced the shortest reading times, fewest and shortest fixations, fewest regressions, and longest progressive saccades, followed by closed squares, and then the unspaced condition. Open squares produced the longest reading times, the most and longest fixations, and the most regressions, but progressive saccade lengths were similar to those for unspaced text.

Table 2 Statistical values for the sentence-level measures

	F_1			F_2		
	df	*F*	η_p^2	*df*	*F*	η_p^2
Sentence Reading Time						
Age	1, 30	20.63***	.407	1, 79	399.56***	.835
Display	3, 90	97.84***	.765	3, 237	120.15***	.603
Age × Display	3, 90	27.81***	.481	3, 237	62.47***	.442
Average Fixation Duration						
Age	1, 30	14.58***	.327	1, 79	597.26***	.883
Display	3, 90	145.99***	.830	3, 237	294.64***	.789
Age × Display	3, 90	22.28***	.427	3, 237	29.11***	.269
Number of Fixations						
Age	1, 30	8.62**	.233	1, 79	243.79***	.755
Display	3, 90	83.16***	.735	3, 237	75.50***	.489
Age × Display	3, 90	19.06***	.395	3, 237	28.18***	.263
Number of Regressions						
Age	1, 30	24.27***	.447	1, 79	423.32***	.843
Display	3, 90	32.00***	.516	3, 237	56.92***	.419
Age × Display	3, 90	17.74***	.372	3, 237	25.10***	.242
Progressive Saccade Length						
Age	1, 30	4.51*	.131	1, 79	316.99***	.800
Display	3, 90	164.38***	.846	3, 237	155.71***	.663
Age × Display	3, 90	12.12***	.288	3, 237	14.87***	.158

† .1 > *p* > .05. * *p* < .05. ** *p* < .01. *** *p* < .001.

To examine whether removing or filling spaces is more disruptive to older than to young adults, a series of repeated measures ANOVAs were conducted in which the size of the age difference was entered as the dependent variable (this was restricted to F_2 analyses, since F_1 analyses were of a mixed design). The main effect of spacing was significant for all measures [reading times, $F_2(3, 237) = 62.47$, $p < .001$; fixation durations, $F_2(3, 237) = 29.11$, $p < .001$; fixation count, $F_2(3, 237) = 28.18$, $p < .001$; number of regressions, $F_2(3, 237) = 25.17$, $p < .001$; and progressive saccade amplitude, $F_2(3, 237) = 14.87$, $p < .001$; see Table 1 for the sizes of the age differences]. Spaced text produced the smallest age difference in reading times and fixation durations and the largest age difference in progressive saccade amplitude, as well as smaller age differences in the number of fixations and regressions than filling spaces with open or closed squares. Although we found few differences in the size of the age effect between the closed-square and unspaced conditions, the open squares produced the largest age difference in reading times, fixation durations, and numbers of fixations and regressions.

Word-level measures

Table 3 shows means for the word-level measures, and Table 4 reports the ANOVA statistics. Main effects of age group, display condition, and word frequency were obtained in all measures (although the effects of age group were only

Table 3 Mean word-level measures for young and older adults in each display condition for high- and low-frequency words

Measure		Normal			Unspaced			Open Squares			Closed Squares		
		High	Low	FE	High	Low	FE	High	Low	FE	High	Low	FE
First- fixation durations (ms)	Young Adults	211 (7)	239 (7)	29	273 (11)	287 (7)	26	243 (9)	291 (11)	42	221 (8)	257 (9)	30
	Older Adults	222 (10)	251 (12)		272 (13)	308 (15)		299 (10)	335 (14)		272 (9)	296 (9)	
	AE	12			9			50			44		
Gaze durations (ms)	Young Adults	226 11)	280 (17)	50	365 (25)	550 (53)	194	297 (14)	444 (30)	152	252 (12)	327 (17)	79
	Older Adults	235 (14)	281 (20)		382 (30)	585 (57)		396 (27)	555 (44)		342 (23)	425 (26)	
	AE	6			23			105			92		
Total reading times (ms)	Young Adults	272 (20)	324 (24)	64	567 (49)	959 (129)	395	354 (25)	548 (40)	249	292 (20)	402 (24)	124
	Older Adults	311 (24)	389 (36)		601 (55)	1000 (93)		548 (40)	853 (62)		448 (36)	587 (47)	
	AE	52			33			247			165		
Regressions in (%)	Young Adults	8.3 (1.9)	8.0 (2.2)	2.3	21.4 (4.6)	28.0 (3.6)	8.0	3.8 (1.3)	9.5 (1.9)	6.8	7.1 (2.6)	11.8 (3.4)	3.0
	Older Adults	17.2 (3.4)	21.9 (4.1)		25.4 (3.6)	34.7 (4.3)		18.3 (3.3)	26.0 (5.6)		19.2 (4.3)	20.7 (4.2)	
	AE	11.3			5.6			15.0			10.8		
Word-skipping rates (%)	Young Adults	9.4 (1.7)	4.4 (1.6)	6.3	2.5 (1.4)	1.9 (1.4)	0.1	1.3 (0.9)	0.6 (0.6)	2.2	6.4 (1.8)	2.6 (1.5)	1.9
	Older Adults	19.0 (4.6)	11.4 (3.3)		6.0 (2.4)	6.5 (2.5)		5.2 (2.2)	1.7 (1.1)		2.6 (1.2)	2.7 (1.6)	
	AE	8.1			4.1			2.3			1.9		

Standard errors are shown in parentheses. AE = age effect, FE = frequency effect

marginally significant by participants for gaze durations and word skipping). Two-way interactions of age group and display condition were found for first-fixation durations, gaze durations (marginally significant by items), total reading times, and skipping rates (marginally significant by items).

For young adults, spaced text produced marginally shortest first-fixation durations, and the shortest gaze durations and total reading times, followed by the closed squares and then the open squares; and unspaced text produced the longest reading times (except for first-fixation durations, which were similar to those for open squares). For older adults, spaced text also produced the shortest first-fixation durations, gaze durations, and total reading times, and unspaced text and open squares produced longer gaze durations and total reading times than did the closed squares. Target words were more likely to be skipped when spacing was normal than when spaces were removed or filled for both age groups (by items only for young adults, as compared with closed squares), and when spaces were removed than when they were filled for the older adults. Supplementary analyses that explored the significant interactions between age group and display condition by entering the age effect as the dependent variable revealed significant main effects of display condition for each measure [first-fixation durations, $F_2(3, 237) = 7.05$, $p < .001$; gaze durations, $F_2(3, 237) = 8.85$, $p < .001$; total reading times, $F_2(3, 237) = 9.65$, $p < .001$; and skipping probabilities, $F_2(3, 237) = 5.65$, $p = .005$; see Table 3]. Pairwise comparisons revealed that this was due to larger age effects for the open and closed squares than for the spaced condition for the reading time measures, and smaller age effects for the open and closed squares than for the spaced condition for skipping probabilities.

Target word frequency significantly interacted with display condition for gaze durations and total reading times. Supplementary analyses that entered the size of the frequency effect as the dependent variable revealed a significant main effect of spacing for these measures [gaze durations: $F_1(3, 93) = 10.29$, $p < .001$; $F_2(3, 237) = 10.30$, $p < .001$; total reading times: $F_1(3, 93) = 14.67$, $p < .001$; $F_2(3, 237) = 16.75$, $p < .001$; see Table 3]. Subsequent pairwise comparisons revealed that this result was due to larger word frequency effects when interword spaces were removed or replaced than for normal text (significant except for the F_1 analyses of gaze duration for the closed squares). However, we found no two-way interactions of age group and word frequency, and no three-way interactions of age group, display condition, and word frequency. Thus, we saw no indication that older adults had more difficulty than young adults identifying words, and no indication of an age-related difference in the influence of removing or replacing interword spaces on the word frequency effect. These findings resonate well with recent findings showing no adult age difference in the size of the word frequency effect for either normal or unspaced text (Rayner et al., 2013).

Discussion

The present findings show that overall older adults read more slowly than young adults; made more and longer fixations, longer progressive saccades, and more regressions; and for target words made marginally longer fixations, more regressions back to target words, and had marginally higher skipping rates. This pattern is broadly consistent with findings

Table 4 Statistical values for analyses of the word-level measures

	F_1			F_2		
	df	*F*	η_p^2	*df*	*F*	η_p^2
First Fixation Duration						
Age	1, 30	7.52**	.200	1, 57	53.41***	.484
Display	3, 90	48.76***	.619	3, 171	26.40***	.317
Frequency	1, 30	75.36***	.715	1, 57	51.02***	.472
Age × Display	3, 90	7.22***	.194	3, 171	4.46**	.073
Age × Frequency	1, 30	0.01	.001	1, 57	0.78	.014
Display × Frequency	3, 90	0.42	.031	3, 171	0.51	.009
Age × Display × Frequency	3, 90	1.17	.038	3, 171	2.04	.035
Gaze Duration						
Age	1, 30	3.72†	.110	1, 57	34.52***	.377
Display	3, 90	74.67***	.173	3, 171	48.30***	.459
Frequency	1, 30	80.95***	.730	1, 57	59.80***	.512
Age × Display	3, 90	5.00*	.143	3, 171	2.69†	.045
Age × Frequency	1, 30	0.08	.003	1, 57	0.79	.014
Display × Frequency	3, 90	9.98***	.250	3, 171	6.87**	.108
Age × Display × Frequency	3, 90	0.07	.002	3, 171	0.67	.012
Total Reading Time						
Age	1, 30	7.23*	.194	1, 62	36.27***	.369
Display	3, 90	62.75***	.677	3, 186	57.74***	.482
Frequency	1, 30	90.73***	.752	1, 62	46.19***	.427
Age × Display	3, 90	4.09*	.120	3, 189	3.54*	.054
Age × Frequency	1, 30	0.99	.032	1, 62	1.50	.024
Display × Frequency	3, 90	14.37***	.324	3, 186	11.74***	.159
Age × Display × Frequency	3, 90	0.37	.012	3, 186	0.20	.003
Regression In						
Age	1, 30	17.63***	.370	1, 66	39.26***	.373
Display	3, 90	16.06***	.349	3, 198	16.78***	.203
Frequency	1, 30	11.87**	.284	1, 66	8.99**	.120
Age × Display	3, 90	1.61	.051	3, 186	1.15	.017
Age × Frequency	1, 30	0.30	.010	1, 66	0.21	.003
Display × Frequency	3, 90	0.65	.021	3, 198	1.41	.021
Age × Display × Frequency	3, 90	0.25	.008	3, 198	0.33	.005
Word-Skipping						
Age	1, 30	3.77†	.112	1, 66	13.49***	.170
Display	3, 90	25.59***	.450	3, 198	20.64***	.238
Frequency	1, 30	6.37*	.175	1, 66	7.27**	.099
Age × Display	3, 90	6.89***	.187	3, 198	2.92†	.042
Age × Frequency	1, 30	0.01	.001	1, 66	0.18	.003
Display × Frequency	3, 90	1.78	.056	3, 198	1.93	.028
Age × Display × Frequency	3, 90	0.68	.022	3, 198	0.55	.008

† $.1 > p > .05$. * $p < .05$. ** $p < .01$. *** $p < .001$.

from previous studies comparing eye movements of young and older adults, and so suggests that readers in the present study performed in a typical fashion (e.g., Kliegl et al., 2004; Rayner et al., 2009; Rayner et al., 2006; Rayner et al., 2013).

The findings for young adults are in line with those reported in previous studies that removed or replaced interword spaces (e.g., Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 1998; Sheridan et al., 2013). As in these studies, young adults had longer reading times, made more and longer fixations, more regressions, and shorter progressive saccades when spaces were removed or replaced, and for target words made more and longer fixations, more regressions, and produced larger word frequency effects. The present findings show that young adults' reading performance was disrupted least by closed squares (which may provide a particularly salient cue to word boundaries), more by open squares (which provide a less salient cue and may induce greater crowding), and most by unspaced text (which provides few cues to word boundaries and may also induce crowding). Older adults also performed better with closed squares than with either open squares or unspaced text, but in contrast to the young adults, they experienced most difficulty with the open squares. Also, consistent with recent findings for unspaced text (Rayner et al., 2013), older readers were disrupted more by the removal or filling of spaces than were young adults. In particular, the size of the difference between the two age groups was much larger for the open than for the closed squares, indicating that older readers can adapt reasonably flexibly to the loss of conventional spaces, so long as other coarse-scale cues to word boundaries are available, but have considerably more difficulty than younger adult readers when these cues are lacking and text is more crowded.

The visual changes that occur naturally in older age lead to a reduction in sensitivity to visual detail and produce increased effects of visual crowding (McCarley et al., 2012; Scialfa et al., 2013; see also Owsley, 2011). As a consequence, older readers may be particularly reliant on coarse-scale cues to the location and physical extent of words in text, and their eye movement performance may be especially prone to the loss of these cues. Indeed, older adults had particular difficulty with open squares, which consisted of fine detail and features (horizontal and vertical lines) that are also found in letters. A number of the older adults commented that they often mistook these symbols for letters, indicating that difficulties in correct identification of the fine detail present in this symbol—and the crowding associated with its features—may have produced inaccurate groupings of features and letters that incorporated features from the delimiter symbol (see Pelli & Tillman, 2008), and so disrupted visual processing even more than unspaced text. Consistent with this explanation, previous research has shown that replacing interword spaces with random letters is more disruptive than simply removing these spaces (Epelboim et al., 1997), very likely because this also produces inaccurate or illusory letter groupings.

In line with the recent findings of Rayner et al. (2013), similar increases in word frequency effects were obtained for young and older adults when spaces were removed. In addition to this, the present study showed that young and older readers also had similar increases in word frequency effects when interword spaces were filled with open or closed squares, indicating that the additional difficulties experienced by the older adults in these conditions were not due to greater difficulty in identifying words. Instead, the pattern of results is more consistent with older readers needing to adopt a more cautious reading strategy when interword spaces are not present. Older adults have previously been described as having a "riskier" reading strategy, in which they are more likely than young adults to guess the identities of words during reading in order to compensate for their poorer processing of text (e.g., Rayner et al., 2006). This strategy may be less effective for text in which clear word boundary information is not available, necessitating a more careful approach. It appears that this cautious strategy was successful, as older adults were able to comprehend text as effectively as young adults when spaces were removed or filled (comprehension accuracy was greater than 95 % for both young and older adults in all conditions). Thus, although normal aging leads to important changes in reading behavior, it seems that older readers can adjust to the visual processing difficulties caused by the loss of conventional cues to word boundaries, so that they continue to comprehend text well.

References

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

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

Elliott, D. B., Yang, K. C., & Whitaker, D. (1995). Visual acuity changes throughout adulthood in normal, healthy eyes: Seeing beyond 6/6. *Optometry and Vision Science, 72,* 186–191.

Epelboim, J., Booth, J. R., Ashkenazy, R., Taleghani, A., & Steinman, R. M. (1997). Fillers and spaces in text: The importance of word recognition during reading. *Vision Research, 37,* 2899–2914.

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

Juhasz, B. J., Liversedge, S. P., White, S. J., & Rayner, K. (2006). Binocular coordination of the eyes during reading: Word frequency and case alternation affect fixation duration but not fixation disparity. *Quarterly Journal of Experimental Psychology, 59,* 1614–1625. doi:10.1080/17470210500497722

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. doi:10.1080/09541440340000213

Malt, B. C., & Seamon, J. G. (1978). Peripheral and cognitive components of eye guidance in filled-space reading. *Perception & Psychophysics, 23,* 399–402.

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

Morris, R. K., Rayner, K., & Pollatsek, A. (1990). Eye guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology. Human Perception and Performance, 16,* 268–281.

Owsley, C. (2011). Aging and vision. *Vision Research, 51,* 1610–1622. doi:10.1016/j.visres.2010.10.020

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

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013a). Aging and the control of binocular fixations during reading. *Psychology and Aging, 28,* 789–795. doi:10.1037/a0033328

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013b). Effects of adult aging on reading filtered text: Evidence from eye movements. *Peer J, 1,* e63. doi:10.7717/peerj.63

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013c). Filtered text reveals adult age differences in reading: Evidence from eye movements. *Psychology and Aging, 28,* 352–364. doi:10.1037/a0030350

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.

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience, 11,* 1129–1135. doi:10.1038/nn.2187

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research, 49,* 1994–2000. doi:10.1016/j.visres.2009.05.009

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology. Human Perception and Performance, 8,* 817–833. doi:10.1037/0096-1523.8.6.817

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., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38,* 1129–1144. doi:10.1016/S0042-6989(97)00274-5

Rayner, K., Reichle, E., Stroud, M., Williams, 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., Yang, J., Schuett, S., & Slattery, T. J. (2013). Eye movements of older and younger readers when reading unspaced text. *Experimental Psychology, 60,* 354–361. doi:10.1027/1618-3169/a000207

Scialfa, C. T., Cordazzo, S., Bubric, K., & Lyon, J. (2013). Aging and visual crowding. *Journals of Gerontology, 68B,* 522–528. doi:10.1093/geronb/gbs086

Sheridan, H., Rayner, K., & Reingold, E. M. (2013). Unsegmented text delays word identification: Evidence from a survival analysis of fixation durations. *Visual Cognition, 21,* 38–60. doi:10.1080/13506285.2013.767296