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# ADULT AGE DIFFERENCES IN THE PERCEPTUAL SPAN DURING READING

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Abstract

Following up on research suggesting an age-related reduction in the rightward extent of the perceptual span during reading (Rayner, Castelhano, & Yang, 2009), we compared old and young adults in an N+2-boundary paradigm in which a nonword preview of word N+2 or word N+2 itself is replaced by the target word once the eyes cross an invisible boundary located after word N. The intermediate word N+1 was always three letters long. Gaze durations on word N+2 were significantly shorter for identical than nonword N+2 preview both for young and for old adults with no significant difference in this preview benefit. Young adults, however, did modulate their gaze duration on word N more strongly than old adults in response to the difficulty of the parafoveal word N+1. Taken together, the results suggest a dissociation of preview benefit and parafoveal-on-foveal effect. Results are discussed in terms of age-related decline in resilience towards distributed processing while simultaneously preserving the ability to integrate parafoveal information into foveal processing. As such, the present results relate to proposals of regulatory compensation strategies older adults use to secure an overall reading speed very similar to that of young adults.

Keywords: age differences, perceptual span, N+2-boundary paradigm, preview benefit, parafoveal-on-foveal effect, compensation strategies

# ADULT AGE DIFFERENCES IN THE PERCEPTUAL SPAN DURING READING

Reading is a highly practiced skill, acquired early in life and used daily throughout the lifespan. In general, eye movements during reading remain remarkably stable in adult age. Recent studies, however, have also revealed some subtle differences pointing towards interesting age-differential dynamics of eye-movement control. For example, old adults fixate words somewhat longer than young adults, but they also skip words more often and perform more regressions back into regions they already inspected (Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). Increased word skipping has been called a more risky strategy (O'Regan, 1990), an attribute usually not associated with old age, but Rayner al al. suggested that old more than young adults might use such a strategy to compensate for their somewhat slower overall reading rate. Old adults might engage more in top-down processing such as guessing the upcoming word on information perceived from not-yet-fixated words in parafoveal vision.

The key to understanding possible age-differential compensation strategies is to determine whether, and if so how, young and old adults differ in the *perceptual span,* that is in the region from which useful information is acquired during reading. The perceptual span is usually measured with the moving window paradigm (McConkie & Rayner, 1975; Rayner & Bertera, 1979) in which, contingent on the current gaze position, a predefined area of text is visible while the rest of the sentence is masked. Such experiments have demonstrated that young skilled readers use information from 3-4 letters to the left and up to 15 letters to the right of a given fixation position to arrive at close to normal reading speed. The asymmetry confirms that the perceptual span during reading is not (only) a visual effect, but is modulated by attentional demands. In fact, it decreases with increasing foveal processing load (Henderson & Ferreira, 1990).

Rayner, Castelhano, and Yang (2009) recently reported a more symmetric perceptual span for old compared to young readers. Using the moving window paradigm, they showed that old readers' perceptual span was reduced in the direction of reading: Given a fixation on word N, young adults benefited from the availability of two parafoveal words N+1 and N+2 (i.e., from a three-word window). In contrast, old adults showed no reduction in their reading speed when only word N and the neighbouring word N+1 were visible and word N+2 was masked (i.e., with a two-word window). In addition, old but not young readers were slowed when word N-1 to the left of the fixated word was masked suggesting a stronger symmetry of the old adults' perceptual span around the fixated word N. Moreover, it seems to be reduced in its rightward extent compared to young adults.

Following up on the rightward-reduction of the perceptual span in old adults, Rayner, Castelhano, and Yang (in press) further investigated the amount of preview old and young readers extract from parafoveal target words during reading. They used the boundary paradigm (Rayner, 1975) in which – during fixations prior to an invisible boundary at the end of word N – word N+1 is either presented as the target word (i.e., an identical preview) or as a random string of letters (i.e., a nonword preview). When the eyes cross the invisible boundary, word N+1 is replaced with the correct target word such that the nonword is never directly fixated. In agreement with extensive research with the N+1-boundary paradigm (for a review see Rayner, 2009), Rayner et al. (in press) observed shorter fixation durations on word N+1 when the identical target word was visible throughout sentence reading. Moreover, this N+1 preview-benefit effect was smaller for old readers, although this age-differential effect was not significant in all fixation duration measures.

Rayner et al. (2009) suggested that the neighboring word N+1 is part of the perceptual span in both age groups, whereas word N+2 is used only by young adults. Therefore, testing preview benefit from the parafoveal word N+2 should show a substantial age effect. The spatial limit of parafoveal processing in young adults was first investigated by Rayner, Juhasz, and Brown (2007) in a study in which they introduced the N+2-boundary paradigm.

In this paradigm, while keeping the invisible boundary located after word N, an additional post-boundary word N+1 preceded the target word N+2.

Although Rayner et al. (2007; experiment 2) used short three- to four-letter words N+1 and N+2 to increase the likelihood that both words fall into the young readers' perceptual span, they did not find any evidence for parafoveal processing of the target word N+2, that is neither a preview-benefit effect on word N+2 nor any other effects in the pretarget region (see also Angele, Slattery, Yang, Kliegl & Rayner, 2008, and Angele & Rayner, 2010, for similar results using a slightly different paradigm). This lack of effects with the N+2-boundary paradigm contrasts with young adults' slower reading speed when word N+2 was masked in the moving-window paradigm (Rayner et al., 2009). The latter result is yet in agreement with Kliegl, Risse, and Laubrock (2007) who reported effects of previewing word N+2 in the N+2-boundary paradigm, using only three-letter words in position N+1.

Given Rayner et al.'s results (2009) one might argue that N+2 preview effects should not be obtained for old adults. However, one could also argue that the chance of finding N+2 preview effects for old adults may actually be higher in the N+2-boundary paradigm. In the moving window paradigm, every word in the sentence may appear as a possible word N+1 relative to the currently fixated word N. As word lengths vary within a sentence, word N+2 will often be deferred further into parafoveal vision. In contrast, in the N+2-boundary paradigm, only very short words are used as pretarget words N+1 to minimize the distance between the pre-boundary fixation and the target word N+2.

In the present study our goal was to investigate age differences in parafoveal processing under conditions of the N+2-boundary paradigm. Therefore, we compared young and old adults using an experimental setup identical to Kliegl et al. (2007). Word N+2 was either presented as an identical or as a nonword preview with the invisible boundary located at the end of the pre-boundary word N (see Figure 1 for an illustration). The post-boundary word N+1 preceding the target word N+2 was always three letters long and varied in its lexical status. In half of the sentences, word N+1 was a function word (i.e., a preposition or conjunction) and in the other half it was a content word (i.e., a noun). The short three-letter function words were of higher printed word frequency than content words. The confound of frequency and type of word is, however, of no concern in the present experiment, because we were only interested in an effective manipulation of processing difficulty of word N+1.

- Figure 1 about here -

The manipulation of processing difficulty of word N+1 allows us to investigate preview effects of parafoveal processing of both words N+1 and N+2 with a single display change. Since preview of word N+1 is not varied across subsequent fixations, identical preview of word N+1 is gained on every fixation. Therefore, we can examine effects of the parafoveal processing difficulty of word N+1 in the pre-boundary fixation on word N. Effects of a parafoveal preview (i.e., of word N+1 or even word N+2) on fixation durations on the currently fixated word N are referred to as parafoveal-on-foveal effects. They are different from preview-benefit effects, which are experimentally induced during fixations on word N, but are measured by definition when the target word N+2 is fixated.

If old adults' perceptual span is more symmetric and significantly reduced in the direction of reading, they should exhibit no or much weaker effects of manipulating preview of word N+2 than young adults. Similarly, parafoveal-on-foveal effects of word N+1 should be attenuated for them as well. Formulated from the perspective of young adults, if their perceptual span is more asymmetric than that of old adults comprising the two parafoveal words N+1 and N+2, they should exhibit effects of previewing word N+2 somewhere within the three-word target region of word N, N+1, or N+2.

## Method

### *Participants*

Forty young and 40 old adults participated in the present study. Young adults were 9 male and 31 female Potsdam University students (age: *M* = 23 years, *SD* = 4) receiving either course credit or 7 € for their one-hour participation. Old adults were 17 male and 23 female members of the Potsdam community (age: $M$ = 71 years, $SD$ = 4) who were paid 10 €. All participants provided informed consent before the start of the experiment.

Subjects wore their glasses to achieve corrected-to-normal vision. Old adults' visual acuity corresponded on average to the normal 20/20 Snellen ratio ($M$ = 1.01, $SD$ = 0.49), but young adults typically reached higher than normal values ($M$ = 1.36, $SD$ = 0.40). Based on acuity data for 30 of 40 old and 13 of 40 young adults, the older participants visual acuity was significantly reduced ($t(41) = 2.44$, $p < .05$). The two groups showed the usual pattern of higher scores for young than old adults in a psychometric measure of processing speed (Tewes, 1991; young: $M$ = 61, $SD$ = 10; old: $M$ = 48, $SD$ = 7; $t(65) = 6.42$, $p < .001$) and slightly but significantly higher scores for old than young adults in a test of vocabulary (Schmidt & Metzler, 1992; young: $M$ = 32, $SD$ = 2; old: $M$ = 33, $SD$ = 2; $t(75) = -3.23$, $p < .01$). Psychometric data were missing from three young adults but were available for all 40 old adults.

*Materials*

A three-word target region (i.e., word N, word N+1, and word N+2) was embedded in simple-structured main clauses without intra-sentential punctuation. Word N ranged from 4 to 13 letters ($M$ = 7) in length, averaging in word frequency to 295 per million. In half of the sentences, the neighbouring word N+1 was a function word (i.e., prepositions or conjunctions) and in the other half a content word (i.e., nouns). In either case, word length was restricted to three letters. Mean frequency of function words averaged to 5,141 per million, and content words were less frequent with 32 per million. Length of word N+2 ranged from four to seven letters ($M$ = 5), with an average frequency of 769 per million. Word-frequency norms were based on the DWDS corpus (Geyken, 2007; Heister et al., 2010) using a reference set of texts of 125 million words.

*Apparatus*

Participants were seated 60 cm in front of the video monitor with their heads positioned in a chin rest to minimize head movements. Reading was binocular and both eyes were monitored with an Eye-Link II system (SR Research, Osgoode, Ontario, Canada). Eye movements were recorded with a 500 Hz sampling rate and an instrument spatial resolution of 0.01°. Sentences were presented on an Iiyama Vision Master Pro 514 monitor (resolution: 1024 x 768 pixel; 21 inch; refresh rate: 150 Hz) using regular Courier New 12 as font resulting in 2.2 characters per degree of visual angle.

*Procedure*

Participants were calibrated using a standard 9-point grid and recalibrated every 15 sentences. Additional calibrations became necessary if detection of the eyes at the initial fixation point prior to each sentence presentation failed within a time window of 2 seconds two times in succession. Participants read 6 practice and 160 test sentences for comprehension and were naive concerning the experimental manipulations. Single sentences were displayed horizontally on the center line of the monitor with a fixed sentence offset from the left monitor border. Before sentence presentation an initial fixation point was displayed designating the word centre of the initial word in each sentence thus varying in its vertical position conditional on the first word's length. Valid detection of the gaze on the fixation point triggered sentence presentation which participants then terminated by fixating a point in the lower right corner. Sentence comprehension was tested on average every third trial by displaying a three-alternative multiple-choice question after completion of sentence reading.

A gaze-contingent display-change technique was implemented for the 160 test sentences. An invisible boundary was placed at the right end of the last letter of a pre-specified word N followed by a three-letter post-boundary word N+1. During pre-boundary fixations, the identical target word N+2 (i.e., identical preview) was presented or a random string of letters (i.e., nonword preview). Nonword previews were generated online. Each letter of the target word N+2 was replaced with a different letter randomly chosen from a set of similar letters matched according to visual similarity in their spatial alignment. As soon as one of the eyes exceeded the boundary location (see below for further details), word N+2 was replaced by the correct target word, being replaced by itself in the identical preview condition. Experimental conditions were counterbalanced across participants. At the end of the experiment, participants were asked whether they had noticed any changes during reading the sentences.

*Data selection*

Data from two young adults were excluded from analyses, one set of data due to technical problems during recording, and the other set because the subject reported to have noticed some display changes during the experiment. For the second reason, we also excluded two old adults. From the remaining 38 young and 38 old adults, 11% of the sentences were lost due to blinks and signal losses. Binocular saccades were detected offline using the algorithm introduced by Engbert and Kliegl (2003; modified by Engbert & Mergenthaler, 2006). While reading was binocular, only right-eye data were analyzed. Data were selected on two levels according to criteria for sentences and individual fixations.

On the sentence level, all sentences were removed in which an invalid display change was detected. Due to system delays within the eyetracker (SR Research Ltd., 2006) and the refresh rate of the monitor not all display changes necessarily had been completed within the forward saccade leaving the pre-boundary word N. To select only those trials with a valid display change (i.e., within the saccade that crossed the boundary) we determined post hoc the exact time of the termination of each trials display change, estimating the time left of the monitor’s refresh cycle at the moment of the first eye crossing the boundary. The delay of the visible display change relative to its trigger averaged to 8.3 ms, ranging from 5 to 11.7 ms. For the analyses, we only considered trials in which the display change on the monitor occurred between the onset and offset of the forward, binocular saccade exceeding the boundary, excluding an additional 18% of the sentences.

On the fixation level of each valid sentence, within-letter refixations (reading microsaccades) were identified and the preceding and following fixation duration were combined. Moreover, invalid fixations within the target region were defined as (i) being shorter than 50 ms or longer than 750 ms, (ii) being the first or last fixation in the sentence, or (iii) when the left eye fixated a different word than the right eye. This last criterion was added in order to exclude cases in which the left eye was ahead of the right eye and might already fixate the parafoveal target word. The dependent measures were generated before excluding invalid fixations. For cumulative fixation duration measures such as gaze durations (see below) we excluded the data point if one of its constituent fixations was invalid. Including both sentence and fixation level criteria, a total of 40 % of the recorded word-based fixations in the target region were excluded (33 % for word N, 53 % for word N+1, 39 % for word N+2) still leaving 6,896 valid GD on word N, 3,289 on word N+1, and 5,988 on word N+2.

*Data analysis*

Separate linear mixed models (LMMs) were estimated for each of the three words in the target region using the *lmer* program (lme4 package; Bates & Maechler, 2010) in the R system for statistical computing (version 2.11.1 R Development Core Team, 2010). Age group was specified as a between-subjects factor (young vs. old adults). The experimental variables such as processing difficulty of word N+1 (easy/function word vs. difficult/content word) and preview of word N+2 (identical vs. nonword preview) were included as within-subject factors. Since the three-letter post-boundary word N+1 was frequently skipped, we also included the binary variable skipping of word N+1 (fixated vs. skipped) in the LMM for fixation durations on the pre-boundary word N and in the LMM for fixation durations on the target word N+2.

All fixed effects were specified with sum contrasts. Therefore, the LMMs return the grand mean dependent variable as intercept and the fixed-effect parameters as deviations from the grand mean. Fixed-effect parameters can be interpreted according to the corresponding main effects and interactions in an ANOVA. Subjects, unique words (i.e., counting the same word in the same and in different sentences only once), and sentences (items) were included as random factors. For each analysis we report the regression coefficients (*b*), the standard errors (*SE*s) and *t* values. A fixed effect is considered significant with absolute *t* values > 2.0 reflecting at least two *SE*s. Fixation durations were log-transformed to achieve near normal distribution of the dependent variables (see Kliegl, Masson, & Richter, 2010).

Results

We report LMMs for log-transformed gaze duration (GD; the sum of all first-pass fixations on a word before the eyes leave to another word). Analyses with untransformed GD revealed the same pattern of effects. The pattern of first fixation durations (FFD; the first fixation of a word during left-to-right reading) was also similar to the one for GD. LMM results with GD as dependent variable are described for each of the three target words. Means for GD and FFD are reported in Table 1 for young and Table 2 for old readers[1].

- Table 1 and Table 2 about here –

*Target word N+2*

*N+2 preview benefit and experimental effects.* As illustrated in Figure 2, the N+2 preview benefit was 18 ms when word N+1 was skipped but decreased to a 5 ms preview cost when word N+1 was fixated (interaction of preview N+2 and skipping N+1: *b* = .07, *SE* = .02, *t* = 4.10). The main effects contributing to this interaction were also significant (i.e., N+2 preview benefit: 6 ms; *b* = .03, *SE* = .01, *t* = 3.28; N+1 skipping cost: 35 ms, *b* = .25, *SE* = .01, *t* = 25.2). The N+2 preview benefit depended also on the processing difficulty of word N+1. N+2 preview benefit amounted to 4 ms after function words N+1 and increased to 9 ms after content words (interaction of preview N+2 and processing difficulty N+1: *b* = .04, *SE* = .02, *t* = 2.13). Spillover of N+1 processing difficulty on the target word N+2 was also significant as a main effect (*b* = .03, *SE* = .02, *t* = 2.02). Finally, skipping cost on word N+2 was larger after easy function words rather than difficult content words N+1 (interaction of skipping N+1 and processing difficulty N+1: *b* = -.13, *SE* = .02, *t* = -7.52). The three-factor interaction involving all experimental variables was not significant (with *t* = -.40). Main effects of skipping cost and spillover of processing difficulty are well established by previous research. The important result here is the reliable N+2 preview benefit after skipping of word N+1 shown in Figure 2, documenting that parafoveal information up to word N+2 is effectively used during reading.

- Figure 2 about here -

*No significant age difference in N+2 preview benefit.* The significant N+2 preview benefit when word N+1 was skipped (see above) was not further modulated by age. Neither the critical three-factor interaction (*b* = -.05, *SE* = .03, *t* = -1.37) nor the subordinate two-factor interaction of age group and preview N+2 (*b* = -.004, *SE* = .02, *t* = -.23) was significant. In fact, post-hoc contrasts in the LMM for the N+2 preview-benefit effect conditional on skipping word N+1 nested within age groups revealed that both young and old adults showed significant N+2 preview benefit if word N+1 was skipped. Young adults showed a 20 ms N+2 preview-benefit effect after skipping word N+1 (*b* = .07, *SE* = .02, *t* = 4.06) which reduced to a non-significant 9 ms preview cost if word N+1 was fixated (*b* = -.02, *SE* = .02, *t* = -.96). Old adults' preview benefit was 16 ms after skipping word N+1 (*b* =.05, *SE* = .02, *t* = 2.62) and not significant if word N+1 was fixated (*b* = -.01, *SE* = .02, *t* = -.56). No other effects reached significance (all absolute *t* values < 1.23). In summary, age revealed no reliable influence on the N+2 preview benefit, which in turn was strongest if word N+1 was skipped. It is important to emphasize that this lack of an age difference occurred in the presence of a significant preview benefit for old adults.

*Age difference in N+1 skipping cost.* Old adults' GD on the target word N+2 were on average 14 ms longer than those of young adults, but this main effect was not significant (*b* = .04, *SE* = .04, *t* = 1.13). The main age-differential result was significantly smaller N+1 skipping cost for old (30 ms) than young adults (42 ms; interaction of age group and skipping

N+1: *b* = -.06, *SE* = .02, *t* = -3.36). This interaction is shown in Figure 3. Old adults appear to not modulate their fixation durations as strongly conditional on whether word N+1 was fixated or skipped as young adults.

- Figure 3 about here -

*Pre-boundary word N*

*Parafoveal-on-foveal effects of N+1 processing difficulty.* GD was 28 ms longer when the upcoming word N+1 was a low-frequency content rather than a high-frequency function word (*b* = .11, *SE* = .02, *t* = 5.48). This is a canonical parafoveal-on-foveal effect of the processing difficulty of word N+1, measured in fixations on the pre-boundary word N. Skipping the upcoming word N+1 significantly modulated pre-boundary GD (*b* = .04, *SE* = .01, *t* = 4.44) and further interacted with processing difficulty of word N+1 (*b* = .04, *SE* = .02, *t* = 2.56). GD on word N prior to function words was 229 ms if word N+1 was then fixated and 226 ms if it was skipped. For content words N+1, this skipping benefit on word N was slightly larger amounting to 7 ms[2]. Finally, preview of word N+2 did not affect GD on word N (*b* = .002, *SE* = .01, *t* = .27).

*Age difference in parafoveal N+1 processing difficulty.* Old adults' GD on word N was 18 ms longer than those of young adults; again, not resulting in a significant age main effect (*b* = .06, *SE* = .04, *t* = 1.52). There was, however, one age-differential effect: The parafoveal-on-foveal effect of the processing difficulty of word N+1 was more pronounced in young than in old adults (*b* = -.06, *SE* = .02, *t* = -3.87). As can be seen in Figure 4, this was mainly due to young adults showing a disproportionate decrease in GD prior to a neighbouring function word N+1. Again, old adults appear to respond less flexibly to non-local processing demand than young adults, that is they were less affected by the processing difficulty of the upcoming word N+1. No other effects were significant (all absolute *t* values < 1.29).

- Figure 4 about here -

*Post-boundary word N+1*

*N+2 preview effect.* GD on the intermediate word N+1 was 4 ms longer when word N+2 was presented in correct preview compared to a nonword preview ($b$ = .04, $SE$ = .01, $t$ = 3.69). Processing difficulty of word N+1 was not significant ($b$ = -.01, $SE$ = .03, $t$ = -.20) and this factor did not interact with preview of word N+2 ($b$ = .03, $SE$ = .02, $t$ =1.47). This result replicates Kliegl et al. (2007) who interpreted the N+2 effect on the post-boundary word N+1 either as a preview benefit in a fixation that was intended for word N+2 (i.e., fixation on word N+1 is a mislocated fixation) or as a parafoveal-on-foveal effect of word N+2 on word N, appearing with delay on the next fixation on word N+1. We will return to this effect in the discussion.

*Age-differential N+2 preview effect.* GD on word N+1 was 23 ms longer for old than young adults ($b$ = .08, $SE$ = .04, $t$ = 2.08). The interaction between age group and N+2 preview was not significant ($b$ = -.02, $SE$ = .02, $t$ = -1.01). Nevertheless, as illustrated in Figure 5, the N+2 preview effect was numerically larger for young than old adults. Post-hoc LMMs for the two age groups suggested that for young adults the 8 ms N+2 preview effect on word N+1 was significant ($b$ = .05, $SE$ = .01, $t$ = 3.41), but the 3 ms effect for old readers was not ($b$ = .03, $SE$ = .02, $t$ = 1.72). With all precaution due to the absence of an age group x N+2 preview interaction, the pattern, again, is consistent with reduced flexibility of old adults' GD with respect to non-local processing demand.

- Figure 5 about here -

## Discussion

We investigated age differences in the perceptual span during reading in the N+2-boundary paradigm. Given a significant rightward-reduction in old adults' span size (Rayner et al., 2009) and previous evidence for N+2 preview effects for young adults (Kliegl et al., 2007) the hypotheses were straightforward: Testing the limits of parafoveal information extraction, young adults should benefit from previewing word N+2 whereas old adults should not. In contrast to this prediction, we found significant preview benefit on the target word N+2 for both age groups. The apparent age-invariance in the rightward extent of the perceptual span (given a short word in position N+1) was further corroborated by old adults showing *decreased* rather than increased "cost" on word N+2 if the previous word N+1 was skipped. Age-differential effects in parafoveal processing were, however, evident in the size of the parafoveal-on-foveal effect of word N+1 in fixations on word N (prior to the boundary) and in the N+2 preview effect on word N+1 (significant only in a post-hoc test) —both effects were *smaller* for old than young adults. Thus, Figures 3 to 5 present three examples of a smaller age difference for conditions with longer gaze durations. These interactions are opposite to the canonical pattern of larger absolute age differences for longer response times.

*Comparison with earlier age-comparative research*

The present research was partly motivated by two earlier studies on age differences in the perceptual span (Rayner et al., 2009; Rayner et al., in press). The lack of an age difference in processing the parafoveal word N+2 differs from a recent finding in a moving window experiment (Rayner et al., 2009) where old adults did not benefit from the availability of word N+2. Since the length of word N+1 varied widely in the Rayner et al. experiment, word N+2 was much more likely to fall outside the perceptual span than in the present study where word N+1 was always three letters long. In this condition, both old and young adults showed some benefit of previewing word N+2. Our results suggest that the word metric by itself does not adequately characterize age differences in the size of the perceptual span; it probably needs to be described both in terms of number of words and number of letters.

The comparable N+2 preview benefit for old and young readers is also difficult to reconcile with a smaller N+1 preview-benefit effect for old adults' GD as reported by Rayner et al. (in press). Since word N+1 is even closer to the pre-boundary fixation, age-related differences should be more pronounced for N+2 than N+1 preview benefit. In the present study, we used long pre-boundary words N to increase the likelihood of fixations and to ensure previewing the target word as an N+2 preview. Indeed, the word length eliminated the typical age difference in skipping word N, which is generally higher in old than young adults (Laubrock, Kliegl, & Engbert, 2006; Rayner et al., 2006). Rayner et al. (in press) also reported an overall age difference of 5% in skipping. If old adults skipped the pre-boundary word N more often by this amount than young adults, the N+1 preview benefit may have collated with some proportion of N+2 preview instead. Age differences in pretarget skipping rates could have compromised the otherwise equally effective preprocessing of word N+1 between age groups.

*No support for age difference in the rightward-extent of parafoveal processing*

With increasing age, visual acuity decreases disproportionately for peripheral vision relative to regions that are closer to the location that is fixated (e.g., Cerella, 1985). In addition, old adults spend somewhat more time in fixating on words (Kliegl et al., 2004; Rayner et al., 2006), possibly reflecting old adults' additional processing demand for encoding a word in foveal vision. The well-established asymmetry of the perceptual span during reading implicates a further contribution of attentional processes, again a domain in which age differences are the rule. Thus, age differences in visual and attentional processing both predict a reduction of the old adults' span size in the direction of reading.

In contrast to this prediction, in our experiment, there was no reliable support for the expectation that old readers were less sensitive to parafoveal information of word N+2 than young readers. In fact, old adults exhibited the same amount of preview benefit on the target word N+2 as young adults. As word N+2 was only separated by a 3-letter word from the current fixation, N+2 was still in the parafoveal range with possibly negligible effects of age-related differences in eccentricity-related drop of visual acuity. The N+2 preview benefit was quite small, averaging only to about one third of what is typically observed for previewing word N+1. However, given word N+2 is more eccentric than word N+1, the size of the N+2 effect in the present study is yet a plausible value. Moreover, the value is in the range of a previous finding (Kliegl et al., 2007). As effects of previewing word N+2 have not been found in other studies (Angele et al., 2008; Angele & Rayner, 2010; Rayner et al., 2007), replicating N+2 preview effects for two age groups was an important goal in itself. Differences between German and English script or in reading strategies may be a source of the discrepant results.

Old adults' preserved processing of word N+2 was also indicated in their comparatively small skipping cost on word N+2. Longer fixation durations after skipping the previous word are typically attributed to reduced preview during the last fixation prior to skipping (Vitu, McConkie, Kerr, & O'Regan, 2001; Radach & Heller, 2000; McDonald, 2005; Reichle, Rayner, & Pollatsek, 2003). If old adults had a smaller span size and thus a disadvantage in processing the parafoveal word N+2, this should result in larger rather than smaller post-skipping cost on word N+2 compared to young adults. Conversely, the age-differential reduction of skipping cost could reflect a lack of resilience in old adults' modulation of fixation durations in response to distributed processing demand during reading. Thus, we propose that there may not be much of an age difference in the rightward extent of the perceptual span, but there may be an age difference in the functional range of fixation durations that are deployed to respond to processing demands or processing opportunities in the perceptual span. We elaborate on this proposal in the next section.

*Age-related differences in modulation of distributed processing demand*

Processing of parafoveal words can manifest itself at two locations. Traditionally, with the boundary paradigm, preview benefit is linked to shorter fixations on the target word after the boundary. In addition, preview processing may also show up as a parafoveal-on-foveal effect on the pre-boundary word. We found no significant age differences in the preview benefit on word N+2, but old adults exhibited a weaker parafoveal-on-foveal effect of word N+1. We propose that this counterintuitive effect pattern is due to two qualitatively different phenomena of parafoveal processing.

Preview benefit is assumed to reflect facilitation due to integrating parafoveally extracted information into later identification processes when a saccade eventually moves the word into foveal vision (Inhoff, 1990; Inhoff & Tousman, 1990). It may reflect a highly automatic process, similar to small or even absent age differences documented for lexical processing (e.g., Lima, Hale, & Myerson, 1991; Mayr & Kliegl, 2000).

In contrast, parafoveal-on-foveal effects are often interpreted in terms of crosstalk due to overlap in parafoveal and ongoing foveal word recognition processes (Kennedy, 1998, 2000). From this latter view, our results seem to indicate that old adults suffer stronger interference from processing words in parafoveal vision, but paradoxically from easy function words N+1. An alternative perspective is that previewing difficult content words in position N+1 affects young adults' foveal word N processing more strongly than that of old adults'. From this perspective older adults' smaller parafoveal-on-foveal effect can be construed, again, as a lack of resilience in adjusting fixation durations to distributed processing demands.

There is another piece of evidence in support of this interpretation, although the effect was only significant in a post-hoc analysis: Preview of word N+2 shortened fixations on word N+1; the amount of shortening was smaller for old than young adults. Kliegl et al. (2007) had reported this effect and offered two explanations: First, the effect could reflect an N+2 preview benefit in a fixation that fell short of its intended target; that is the fixation was actually planned for word N+2, but due to failed skipping is observed on word N+1. Such mislocated fixations – if not immediately corrected – should then reflect processing the attended rather than the fixated word (Drieghe, Rayner, & Pollatsek, 2008; for contrary results see Kennedy, 2008).

The second explanation is in terms of a delayed parafoveal-on-foveal effect spilling over into fixation durations on word N+1. Given the word N+2 distance, availability of processing difficulties might be delayed (Lee, Legge, & Ortiz, 2003) leading to later effects than word N+1. This might be a parsimonious explanation for why we did not observe a parafoveal-on-foveal effect of word N+2 in fixations on word N although word N+2 was apparently previewed during those fixations. At this point, the nature of this very reliable N+2 effect is not clear, but results from ongoing research are in support of a delayed parafoveal-on-foveal effect (Risse & Kliegl, in preparation)[3]. Importantly for the present context, the tendency towards an age-related reduction of a delayed parafoveal-on-foveal effect of word N+2 is compatible with the proposition of an age-differential lack of resilience. Old adults may not exploit the processing opportunity to the same extent as young adults.

Our proposal of age-related lack of resilience in modulating fixation durations in response to processing opportunities in the perceptual span, shown in the three non-canonical age by condition interactions displayed in Figures 3 to 5, can also be linked to an age difference in the inhibition parameter of the SWIFT model (Laubrock et al., 2006). In this study, the authors argued that weaker inhibition in older adults leads to less modulation in their fixation durations compared to young adults. In turn, this age difference is also roughly compatible with the assumption of impaired inhibitory control processes with aging (Hasher Stoltzfus, Zacks, & Rypma, 1991).

*Two perspectives: Low-level and high-level compensatory strategies*

The joint observation of an apparent age invariance and a significant age difference invites speculations about compensatory strategies in cognition. Our proposal of an age difference in modulation of distributed processing demands in the perceptual span offers bridges to two areas of research in which the pursuit of age-differential compensatory strategies has taken center stage. How do old adults compensate for well-documented disproportionate decline in peripheral visual acuity? And how do old adults maintain a reading and comprehension rate comparable to that of young adults despite disproportionate decline in working-memory related executive control?

The present results suggest age invariance in the rightward-extent to which parafoveal information is accessed during reading (i.e., up to word N+2 for both age groups). Although young adults had higher values in a standard visual acuity test, old readers' perceptual span on average also included word N+2. Therefore, the perceptual span in reading is probably more closely related to the distribution of attention (Engbert & Kliegl, 2010; Henderson & Ferreira, 1990; Rayner & Pollatsek, 1987) than to physiological constraints of visual acuity. Indeed, dynamical modulation of attention deployment may help to compensate for age-related limitations of visual acuity, particularly in parafoveal vision. Exactly how individual differences in visual acuity, specifically in parafoveal vision, contribute to the perceptual span is an important topic for further research. As a first step, standard Snellen-chart tests should probably be supplemented with refined assessments of foveal, parafoveal, and peripheral visual acuity. A 20/20 score for both young and old adults certainly does not establish equal visual acuity for the two age groups.

Age-comparative reading research has delivered several examples how old adults maintain the same overall reading rate as young adults despite deficits in low-level processing. Old adults are better in detecting a letter in syntactically intact compared to scrambled sentences (Allen, Stadtlander, Groth, Pickle, & Madden, 2000). Since old adults were slower in recognizing individual words, the authors argued that stronger sentence-level codes, possibly mediated by parafoveal processing, allowed them to maintain a reading rate comparable to those of young adults. In reading sentences with ambiguous relative clauses, old adults exhibited more regressions than young adults while maintaining the same overall reading times (Kemper, Crow, & Kemtes, 2004). There are also tradeoffs between early wrap-up processing in old and late wrap-up processing in young adults at salient clause boundaries (Stine-Morrow et al., 2010). Their strategy may allow old adults to reduce their burden on memory and facilitate their success of comprehension. Of course, age differences in the perceptual span are likely tied up with such compensatory strategies.

In conclusion, how acuity differences, specifically in parafoveal vision, on the one hand, and presumably high-level regulatory strategies, on the other, interact with age differences in modulation of distributed processing demands in the perceptual span remains a promising topic for future research.

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Footnote

1. Condition means for all tables and figures were computed over all respective data points. In contrast to ANOVAs in which effects are estimated on the level of aggregated condition means, differences between subjects are captured in the simultaneously estimated LMM variance component. Although not identical, the condition means computed here more closely reflect the LMM approach.
2. This result contributes positive evidence to the discussion of skipping benefit rather than cost prior to short words (Kliegl & Engbert, 2005).
3. The finding of N+2 preview benefit mainly after skipping word N+1 in the present study favours the argument that failed skipping “mimics” an N+2 preview benefit in mislocated fixations on word N+1. However, the preview benefit on the target word N+2 was also larger if the previous word N+1 was a more difficult content word rather than a high-frequent function word, contrary to the evidence for parafoveal load reducing N+2 preview benefits in Chinese (Yan, Kliegl, Shu, Pan, & Zhou, in press). With respect to a related discussion, this finding is difficult to reconcile with serial attention shifts during reading. Overall, our results are consistent with Wang, Inhoff, and Radach (2009) who also observed non-locally distributed preview effects arguing against a strict confinement to processing only one word at a time.

Table 1.

*Young adults' means and standard deviations on word N, N+1, and N+2.*

| | | **FFD** | | | | **GD** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Skipping of word N+1 | | | | Skipping of word N+1 | | | |
| | | fixated | | skipped | | fixated | | skipped | |
| Difficulty of word N+1 | Preview of word N+2 | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| | | **Measured on word N+2** | | | | | | | |
| easy (FW) | identical | 198 | 74 | 220 | 59 | 210 | 87 | 248 | 84 |
| | nonword | 190 | 62 | 226 | 65 | 195 | 69 | 266 | 86 |
| difficult (CW) | identical | 216 | 84 | 206 | 65 | 226 | 98 | 242 | 95 |
| | nonword | 216 | 81 | 221 | 69 | 223 | 89 | 266 | 107 |
| | | **Measured on word N+1** | | | | | | | |
| easy (FW) | identical | 211 | 72 | | | 211 | 73 | | |
| | nonword | 217 | 79 | | | 218 | 79 | | |
| difficult (CW) | identical | 209 | 65 | | | 209 | 65 | | |
| | nonword | 215 | 63 | | | 217 | 65 | | |
| | | **Measured on word N** | | | | | | | |
| easy (FW) | identical | 206 | 53 | 197 | 59 | 217 | 72 | 211 | 76 |
| | nonword | 204 | 61 | 196 | 59 | 217 | 79 | 214 | 78 |
| difficult (CW) | identical | 216 | 65 | 212 | 77 | 253 | 98 | 250 | 109 |
| | nonword | 210 | 64 | 214 | 73 | 248 | 99 | 251 | 112 |

*Note.* FW: function word; CW: content word; FFD: first fixation duration; GD: gaze duration; M: mean value; SD: standard deviation

Table 2.

*Older adults' means and standard deviations on word N, N+1, and N+2.*

| | | **FFD** | | | | **GD** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Skipping of word N+1 | | | | Skipping of word N+1 | | | |
| | | fixated | | skipped | | fixated | | skipped | |
| Difficulty of word N+1 | Preview of word N+2 | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| **Measured on word N+2** | | | | | | | | | |
| easy (FW) | identical | 216 | 92 | 238 | 81 | 229 | 107 | 266 | 103 |
| | nonword | 209 | 83 | 243 | 82 | 219 | 98 | 276 | 113 |
| difficult (CW) | identical | 234 | 93 | 213 | 73 | 243 | 101 | 243 | 103 |
| | nonword | 238 | 94 | 229 | 80 | 245 | 98 | 267 | 126 |
| **Measured on word N+1** | | | | | | | | | |
| easy (FW) | identical | 238 | 92 | | | 239 | 94 | | |
| | nonword | 232 | 79 | | | 235 | 80 | | |
| difficult (CW) | identical | 232 | 87 | | | 234 | 91 | | |
| | nonword | 240 | 88 | | | 241 | 88 | | |
| **Measured on word N** | | | | | | | | | |
| easy (FW) | identical | 228 | 74 | 219 | 79 | 241 | 85 | 239 | 96 |
| | nonword | 227 | 74 | 221 | 79 | 242 | 93 | 241 | 95 |
| difficult (CW) | identical | 235 | 87 | 215 | 72 | 265 | 108 | 256 | 113 |
| | nonword | 234 | 84 | 214 | 76 | 265 | 112 | 249 | 107 |

*Note.* FW: function word; CW: content word; FFD: first fixation duration; GD: gaze duration; M: mean value; SD: standard deviation

*Figure 1*. Illustration of the N+2-boundary paradigm and its three-word target region. Below a German example sentence with an English translation for the two N+2 preview conditions. Relative to the gaze position (asterisks) the display change of word N+2 is triggered.

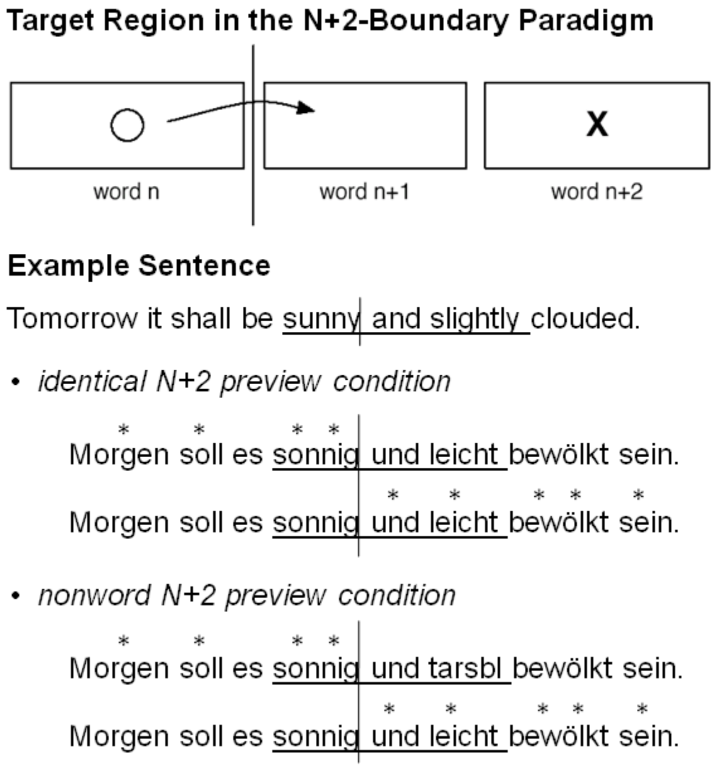

*Figure 2.* Difference in N+2 preview benefit conditional on skipping word N+1. Plotted is the mean GD on the target word N+2 for the N+2 preview conditions by skipping the preceding word N+1. Error bars represent the 95 % confidence interval.

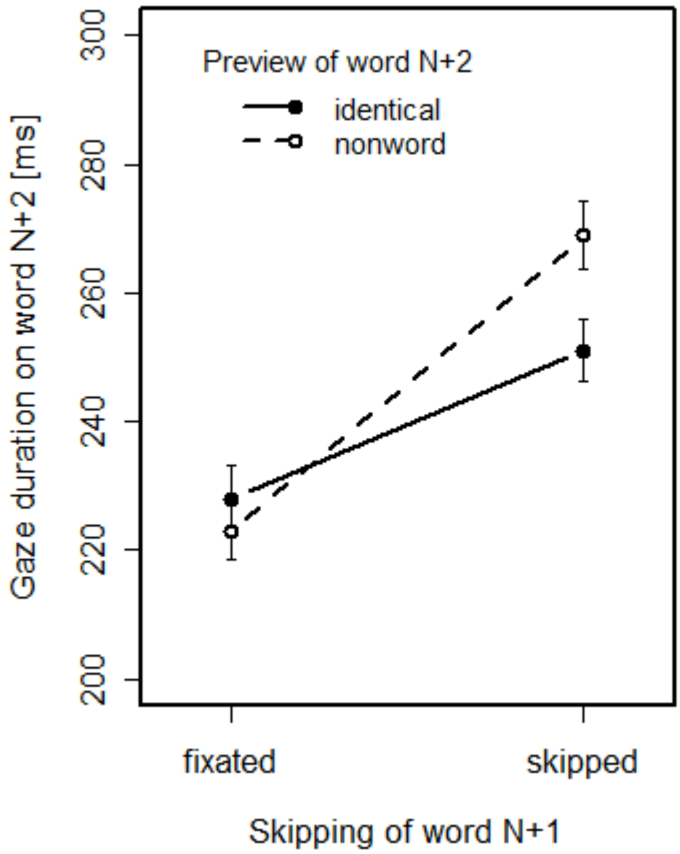

*Figure 3*. Age difference in post-skipping costs. Plotted is the mean GD on the target word N+2 conditional on skipping the preceding word N+1, both for young and old adults. Error bars represent the 95 % confidence interval.

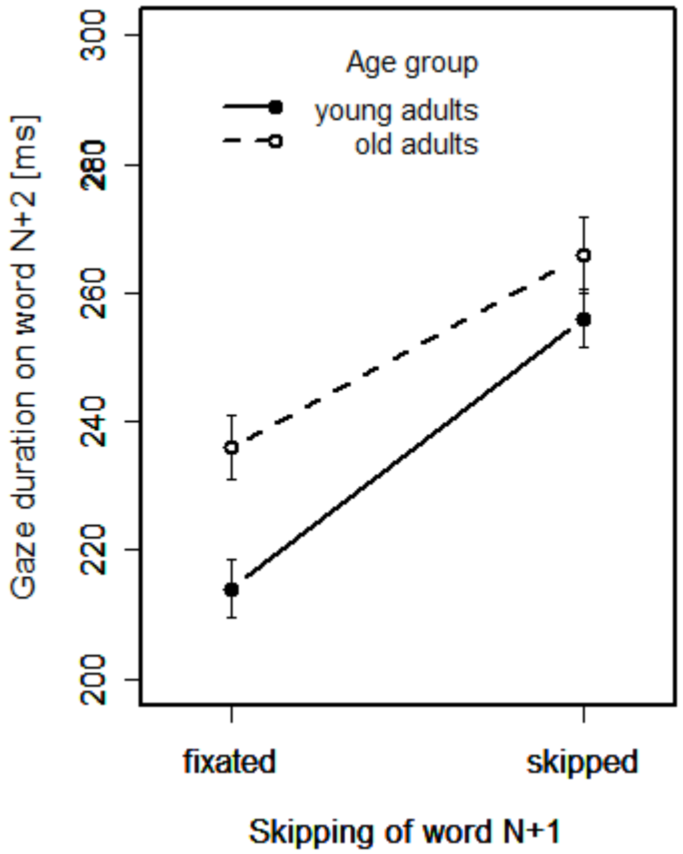

*Figure 4.* Age difference in the parafoveal-on-foveal effect of the neighbouring word N+1. Plotted is the mean GD on the pre-boundary word N depending on the processing difficulty of word N+1, both for young and old adults. Error bars represent the 95 % confidence interval. FW: function word; CW: content word.

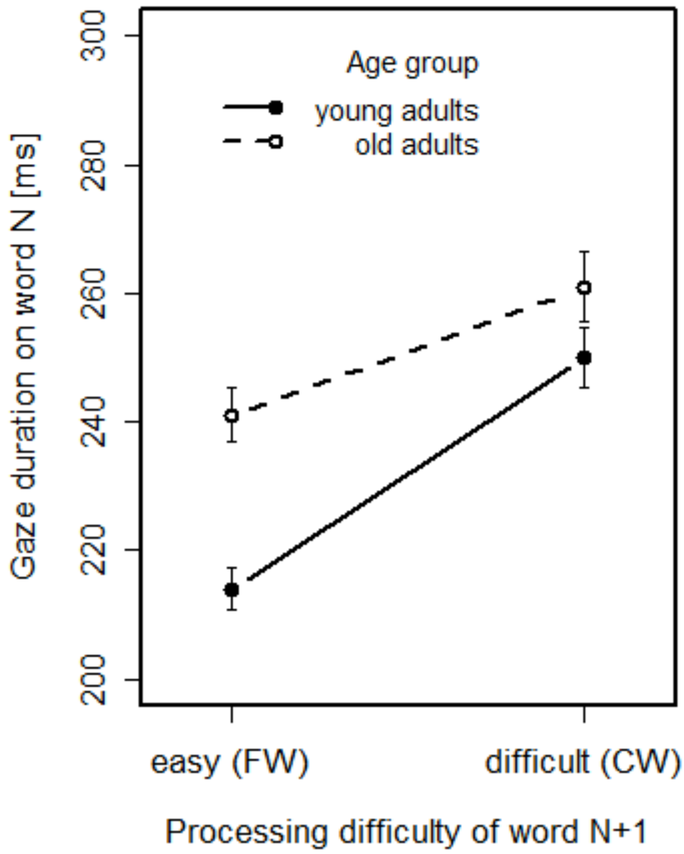

*Figure 5.* N+2 preview effect on the post-boundary word N+1. Plotted is the mean GD on word N+1 conditional on the preview condition of word N+2 for young and old adults. Error bars represent the 95 % confidence interval.