# Reading performance in middle-aged adults with declines in accommodation

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**Abstract** The present study investigated the effects of presbyopia on the reading ability of middle-aged adults in a Japanese reading context, using the rapid serial visual presentation paradigm. Japanese words, each consisting of three characters, were sequentially presented at the same location on a display screen. Participants were instructed to read the words aloud as accurately as possible, irrespective of their order within the sequence. Experiment 1 showed that the reading performance for the presbyopes was far worse for the near-viewing (35 cm) than for the far-viewing (70 cm) conditions when the words were presented at 0.4° in character size. Experiment 2 investigated in detail the effect of luminance contrast on reading at a viewing distance of 35 cm. The minimums of the exposure durations within which the participants could read the words above 89.9 % correct (minimum exposure duration) were 498 ms/word for the presbyopes and 134 ms/word for the nonpresbyopes, both of which values were obtained at 100 % contrast. The critical contrast—that is, the contrast that doubled the minimum exposure duration that had been obtained at 100 % contrast—was considerably higher for the presbyopes (39.2 %) than for the nonpresbyopes (16.4 %). However, the reading performance for the presbyopes was improved more than threefold when the contrast was increased to 100 % in both experiments. Thus, our results provide psychophysical evidence for the dependency of presbyopes' reading on viewing distance and luminance contrast.

**Keywords** Aging · Reading · Decline in accommodation

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Reading is a fundamental function to facilitate intellectual activities from a very young to a very old age and is of particularly great importance for our daily communication. Many previous studies have investigated the properties of the visual mechanisms underlying reading performance and have reported several key parameters affecting reading text, such as character size (Legge & Bigelow, 2011; Legge, Pelli, Rubin, & Schleske, 1985), contrast (Legge, Rubin, & Luebker, 1987; Rubin & Legge, 1989), spatial frequency (Legge et al., 1985), word length (Legge, Ahn, Klitz, & Luebker, 1997; Legge, Mansfield, & Chung, 2001), and eccentricity on the retina (Chung, Legge, & Cheung, 2004; Legge et al., 1997, 2007, 2001; Yu, Cheung, Legge, & Chung, 2007), as well as close relations to eye movements (Rayner & Inhoff, 1981) and working memory function (Daneman & Carpenter, 1980). However, relatively less is known about age-related changes in reading.

As we become older, several visual functions related to reading decline. For example, declines are observed in spatial contrast sensitivity (e.g., Derefeldt, Lennerstrand, & Lundh, 1979; Owsley, Sekuler, & Siemsen, 1983; Wright & Drasdo, 1985; see also Owsley, 2011, for a review), motion perception (e.g., Trick & Silverman, 1991; Wood & Bullimore, 1995), binocular vision (e.g., Faubert & Overbury, 2000), orientation discrimination (e.g., Betts,

Sekuler, & Bennett, 2007), and so on (see Faubert, 2002, and Sekuler & Sekuler, 2000, for a review). Not only such perceptual abilities, but also the optical system, the very entrance of the visual system, shows a decline in function with age. Retinal illuminance in older eyes is reduced due to smaller pupil size (Hennelly, Barbur, Edgar, & Woodward, 1998; Loewenfeld, 1979), increased density of the crystalline lens (Pokorny, Smith, & Lutze, 1987; Said & Weale, 1959; Weale, 1961), increased intraocular light scatter, and increased optical aberrations (Artal, Guirao, Berrio, Piers, & Norrby, 2003; Glasser & Campbell, 1998). The most frequent symptom is a gradual decrease of accommodative power, resulting in presbyopia (see Strenk, Strenk, & Koretz, 2005, for a review). This reduction in accommodation is assumed to be caused by increasing lens thickness (Strenk et al., 2005); it begins quite early in life and becomes salient by around the age of 50 years (McDonnell, Lee, Spritzer, Lindblad, & Hays, 2003). This causes reduced visual acuity with near viewing, making it difficult to read letters.

A few studies have demonstrated an age-related decline in reading (Akutsu, Legge, Ross, & Schuebel, 1991; Yu, Cheung, Legge, & Chung, 2010), although the effect has been less pronounced than those in other areas of visual performance. Akutsu et al. investigated the influence of character size on the reading speeds of elderly participants (aged 60–74 years) by using a drifting-text method. They found that elderly participants with healthy eyes and their accommodation corrected to normal were able to read as fast as young participants (aged 19–30 years) for character sizes ranging from 0.3° to 1.0°. A decline in reading speed was observed only for very small (0.15°) or very large (4.0° and 12.0°) characters—at these character sizes, the elderly participants' reading speeds dropped to about 70 % of those of the young participants. The authors considered that age-related losses in contrast sensitivity for higher and lower spatial frequencies might explain these results. Yu et al. (2010) reported that training to enlarge visual span (i.e., the number of characters on a line of text that can be recognized accurately in one fixation) improved reading speed among older adults (ages 55–76), although the training effects were a little weaker for older than for younger adults (Chung et al., 2004).

The present study further investigated the age-related declines in reading performance, focusing on reduced accommodation due to aging and a Japanese reading context. In general, aging of the optical and perceptual systems leads to declines of visual function. In the aforementioned studies on age-related declines in reading (Akutsu et al., 1991; Yu et al., 2010), the participants' eyes were corrected by glasses or contact lenses so that the authors could single out decline of the perceptual

system in terms of reading. Thus, it is yet unclear psychophysically how aging of the optical system can affect reading performance. In particular, a decline in accommodation, or presbyopia, is common in populations of over 50 years of age, who suffer from a diminished ability to focus on near objects and difficulties in reading. Furthermore, few studies have focused on the relationship between presbyopia and reading in Japanese. The Japanese writing system is unique, consisting of three types of symbols: hiragana, katakana, and kanji. Each hiragana and katakana character is a phonogram and represents either a vowel or one mora, which phonologically represents a combination of a consonant and a vowel, with a few exceptions (see Fig. 1 below for examples of hiragana). These characters are similar in usage to the letters of English. Chinese characters (kanji), on the other hand, are logograms, often correspond to several morae, look more complicated, and contain more components of high spatial frequency than do hiragana and katakana characters (see Fig. 2 below; cf. Osaka, 1992). Daily Japanese texts are mostly written in a mixture of kanji and hiragana characters rather than only in hiragana. In the present study, we used hiragana (Exp. 1) and a mixture of hiragana and kanji (Exp. `2) for the stimuli.

In Experiment 1, we investigated how viewing distance would affect reading performance, while simultaneously manipulating character size and luminance contrast. In Experiment 2, we investigated the effect of luminance contrast in detail, because contrast is one of the important factors for reading, in normal vision as well as in low vision (Legge et al., 1987; Rubin & Legge, 1989). In both experiments, we used the rapid serial visual presentation (RSVP) paradigm to avoid the potential influences of oculomotor control (Chung, Mansfield, & Legge, 1998; Rubin & Turano, 1992) and aging in eye movements (Sharpe & Sylvester, 1978; Spooner, Sakala, & Baloh, 1980). In the RSVP paradigm, individual words were presented sequentially at the same location on a display screen. The RSVP rate was controlled by adjusting the exposure duration for each word. Furthermore, we



(a) きけん　　(f) すでに
(b) きれい　　(g) きせつ
(c) はなび　　(h) すごい
(d) およぐ　　(i) りかい
(e) にくむ　　(j) いわう

**Fig. 1** Samples of the words used in Experiment 1. All words consisted of three letters of hiragana and were rendered in MS Gothic in black on a white background. The meaning and pronunciation of each word is shown in Table 3

| (a) 地下水 | (f) 単なる |
|---|---|
| (b) 優しい | (g) 自動車 |
| (c) 政治家 | (h) 厳しい |
| (d) 費やす | (i) 水平線 |
| (e) 用いる | (j) 数える |

**Fig. 2** Samples of the words used in Experiment 2. All of the words used were written in a mixture of kanji and hiragana and were rendered in MS Gothic in black on a white background. The meaning and pronunciation of each word is shown in Table 5

targeted middle-aged adults in order to single out the effects of declines in accommodation, assuming that most middle-aged adults would not suffer from any eye disorders other than presbyopia—such as macular degeneration, cataracts, and glaucoma—or, likewise, from perceptual dysfunctions (and, in fact, our participants did not suffer from such eye disorders or perceptual dysfunctions).

## Experiment 1

### Method

*Participants* A total of 12 presbyopic participants (47–54 years of age, with a median of 49.9; 11 females and 1 male) took part in this experiment, along with the same number of younger, nonpresbyopic participants (19–25 years, with a median of 22.3; 5 females and 7 males). Tables 1 and 2 show each participant's age, gender, and (myopia-corrected) visual acuity. The amplitude of accommodation for the presbyopes is also shown. Visual acuity was measured by using the international standard Landolt Ring chart. All of the presbyopic participants were aware of their symptoms but did not report any other defects in vision (e.g., macular degeneration, cataract, or glaucoma). Also, ophthalmologists diagnosed that all of the older participants had presbyopia but no other identifiable pathology. While those who had myopia were corrected by spectacles or contact lenses, presbyopic corrections were not allowed during the experiments. Even for the short-viewing-distance condition (35 cm), the presbyopes wore myopia-correcting lenses if needed. All were native Japanese speakers. This study followed the tenets of the Declaration of Helsinki, and the protocol was approved by the ethics committee of Kyushu University. Written informed consent was obtained from all of the participants prior to participation.

*Experimental design* Two viewing distance conditions were tested: 35 and 70 cm. These distance conditions were determined from preliminary experiments and our daily observations that, without accommodation correction, presbyopes have difficulty reading books and newspapers, which are generally located around a viewing distance of 40 cm. We thus predicted that the effect of viewing distance would be pronounced only for the presbyopic participants. Additionally, character size (0.4° and 1.0°) and contrast (10 % and 100 %, Michelson contrast) were included as independent variables. Akutsu et al. (1991) reported that elderly

**Table 1** Eye condition/acuity of presbyopes (N = 12) for Experiment 1

| Participant | Age | Sex | Acuity (3 m) | | | Amplitude of Accommodation (D) | |
|---|---|---|---|---|---|---|---|
| | | | L | R | Binocular | L | R |
| A | 54 | F | 0.7 | 0.7 | 0.9 | 0.94 | 0.61 |
| B | 53 | F | 0.8 | 0.7 | 0.9 | 1.62 | 1.60 |
| C | 49 | F | 0.7 | 0.8 | 1.0 | 1.21 | 1.17 |
| D | 48 | F | 1.0 | 1.0 | 1.2 | 2.0 | 1.97 |
| E | 52 | F | 1.0 | 1.0 | 1.2 | 1.41 | 1.37 |
| F | 47 | F | 1.0 | 1.0 | 1.2 | 1.72 | 1.33 |
| G | 54 | F | 0.8 | 0.6 | 1.0 | 1.14 | 1.16 |
| H | 52 | F | 0.6 | 0.6 | 0.8 | 1.32 | 1.42 |
| I | 47 | F | 0.9 | 0.1 | 0.9 | 1.7 | 1.6 |
| J | 49 | M | 1.2 | 1.2 | 1.2 | 1.41 | 1.39 |
| K | 51 | F | 0.3 | 0.3 | 0.7 | 1.26 | 1.32 |
| L | 53 | F | 0.9 | 0.5 | 1.0 | 1.28 | 1.26 |

"Acuity" is decimal acuity for distance vision, in which 20/20 is 1.0 and 20/40 is 0.5

**Table 2** Eye condition/acuity of nonpresbyopes (N = 12) for Experiment 1

| Participant | Age | Sex | Acuity (3 m) | | |
|---|---|---|---|---|---|
| | | | L | R | Binocular |
| M | 23 | M | 0.5 | 0.5 | 0.8 |
| N | 23 | M | 0.3 | 0.5 | 1.2 |
| O | 23 | M | 0.8 | 1.0 | 1.2 |
| P | 23 | M | 1.5 | 1.2 | 1.5 |
| Q | 23 | F | 1.0 | 0.9 | 1.0 |
| R | 22 | F | 1.2 | 0.9 | 1.2 |
| S | 22 | F | 0.9 | 1.0 | 1.2 |
| T | 25 | M | 0.9 | 1.0 | 1.2 |
| U | 19 | F | 0.5 | 0.3 | 0.6 |
| V | 22 | M | 1.2 | 0.9 | 1.2 |
| W | 21 | M | 0.9 | 0.7 | 1.2 |
| X | 21 | F | 1.5 | 1.2 | 1.2 |

"Acuity" is decimal acuity for distance vision, in which 20/20 is 1.0 and 20/40 is 0.5, and was measured with (myopia) corrections

participants with no anomalies in their eyes read as fast as young participants for character sizes ranging from 0.3° to 1.0°. However, they tested only in a high-contrast condition. Previous studies have reported an interaction between character size and contrast (Legge et al., 1985, 1987). For characters presented at high contrast, reading performance has been reported to be almost independent of character size between 0.3° and 2.0° for normal vision. At low contrast (less than 10 %), on the other hand, reading performance declines slightly for small character sizes of around 0.5°, and rapidly declines as the size becomes very small (<0.25°) (Legge et al., 1987). We thus predicted that an effect of character size would be observed at low contrast. In sum, we presented eight stimulus conditions [2 (viewing distance: 35 and 70 cm) × 2 (character size: 0.4° and 1.0°) × 2 (contrast: 10 % and 100 %)] for each participant group.

*Stimuli* Visual stimuli were generated using a visual stimulus generator (ViSaGe; Cambridge Research Systems, U.K.) attached to an IBM-compatible personal computer (Dell PRECISION 390) and displayed on a γ-corrected 19-in. color monitor (EIZO, Flex Scan T760; refresh rate 65 Hz, resolution 1,600 × 1,200). All visual stimuli were presented in the center of the monitor.

All of the words used were selected within the range of high word familiarity—that is, over 5.4 (maximum: 7) in the Japanese familiarity-controlled word lists (Amano & Kondo, 2003). In each trial, test words were chosen randomly from a pool of 1,598 words. All of the words were presented in hiragana only and containing three hiragana characters. Examples include *ka-o-ri* ("smell of something"), *ta-i-ko* ("drum"), and so on (see also Fig. 1 and Table 3). Words generally written in katakana or containing demonstratives (i.e., terms such as "this," "that," and "it") were excluded from the candidates. The words were rendered in MS Gothic Japanese, a fixed-width font, and were

**Table 3** Samples of Japanese words used in Experiment 1

| Word | Pronunciation | Word Class | Meaning |
| --- | --- | --- | --- |
| (a) | ki-ke-n | noun | danger |
| (b) | ki-re-i | adjective | beautiful or clean |
| (c) | ha-na-bi | noun | firework |
| (d) | o-yo-gu | verb | swim |
| (e) | ni-ku-mu | verb | hate |
| (f) | su-de-ni | adverb | already |
| (g) | ki-se-tsu | noun | season |
| (h) | su-go-i | adjective | amazing |
| (i) | ri-ka-i | noun | understanding |
| (j) | i-wa-u | verb | cerebrate |

The appearance of each word is shown in Fig. 1

presented as black characters on a white background of 121.0 cd/m².

*Procedure* Experiments were conducted with binocular viewing in a dark room. The RSVP paradigm was used to measure reading performance (Chung et al., 1998). Immediately after a participant's buttonpress, a warning tone was presented for 600 ms, followed by presentation of a black fixation point (0.18° in diameter) at the center of the monitor for 500 ms. Two hundred milliseconds after the disappearance of the fixation point, three Japanese words were displayed consecutively, one word at a time, in the same position. The participants were instructed to read the words aloud as accurately as possible, irrespective of the word order within the sequence. They were allowed to complete their verbalization during the presentation of the words as well as after the word had disappeared from the display. The experimenter assessed their responses and entered the number of correct responses into the computer. Immediately after that, a warning tone was presented for 600 ms, and the next trial began.

The initial exposure duration of each word was determined according to the performance of each participant in the preliminary trials, so that it was sufficiently long for each participant to easily report all of the words. In subsequent trials, the exposure duration varied from trial to trial according to a staircase method (Cornsweet, 1962). The exposure duration was decreased when eight or nine words out of nine presented (3 words × 3 trials) were reported correctly (89.9 % correct). The exposure duration was decreased by 83 ms for the first decrement, by 50 and 33 ms for the second and third decrements, respectively, and by 17 ms for subsequent decrements. Conversely, the exposure duration was increased by 17 ms when the number of words correctly reported was less than eight out of nine words. The staircase was terminated after ten reversals of the exposure duration sequence. The threshold of the exposure duration was calculated as the average of all but the first two reversals.

Different viewing distances were tested in different blocks. Half of the participants performed the 35-cm viewing distance block first, and the other half performed the 70-cm viewing distance block first.

## Results and discussion

Figs. 3a and b show the average thresholds of exposure duration across participants at the 35-cm and 70-cm viewing distances, respectively, in Experiment 1. Because one participant in the presbyopic group (participant A in Table 1) failed to perform the task with 0.4° characters written with 10 % contrast in the 35-cm viewing condition, her data were removed from the subsequent analysis.

**A** Viewing Distance: 35 cm
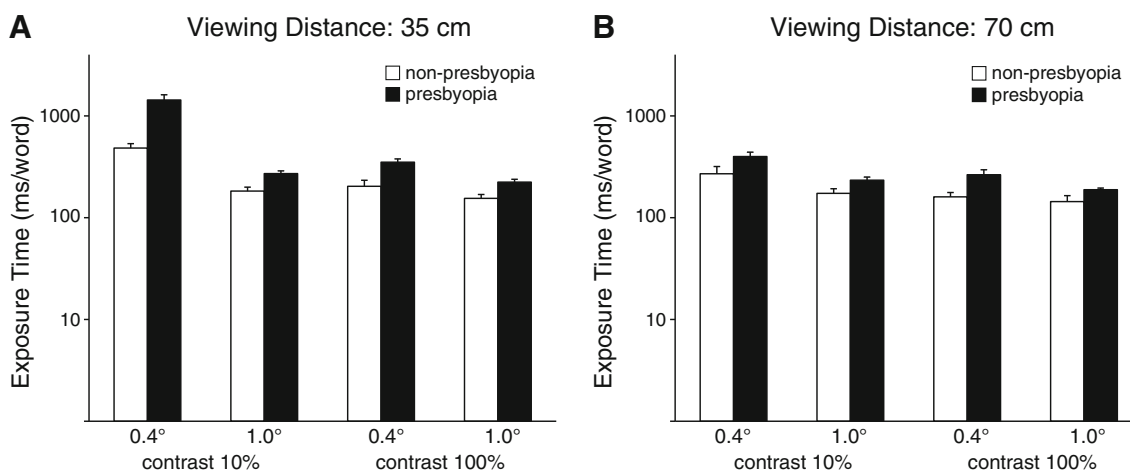


**B** Viewing Distance: 70 cm



Fig. 3 Thresholds of exposure duration (ms/word) for the 35-cm (A) and 70-cm (B) viewing conditions. The vertical axis indicates the threshold of exposure duration (ms/word), while the horizontal axis indicates character size (in degrees) and contrast (as percentages). The white and black bars represent the data of nonpresbyopes and presbyopes, respectively. Error bars denote the standard errors of the means

The thresholds of the exposure duration were analyzed in a four-way mixed analysis of variance (ANOVA) with the factors Group (presbyopes and nonpresbyopes), Viewing Distance (35 and 70 cm), Contrast (10 % and 100 %), and Character Size (0.4° and 1.0°). Significant main effects of all of these factors were observed [group, $F(1, 21) = 30.30$, $p < .001$, $\eta^2 = .086$; viewing distance, $F(1, 21) = 46.70$, $p < .001$, $\eta^2 = .070$; contrast, $F(1, 21) = 76.18$, $p < .001$, $\eta^2 = .101$; and character size, $F(1, 21) = 97.25$, $p < .001$, $\eta^2 = .131$]. All of the interactions were also significant [one-way interactions, $Fs(1, 21) > 18.18$, $ps < .001$; two-way interactions, $Fs(1, 21) > 20.65$, $ps < .001$; three-way interaction, $F(1, 21) = 23.08$, $p < .001$, $\eta^2 = .021$]. The post-hoc tests for the three-way interaction revealed that the presbyopes' reading performance was significantly worse than that for the nonpresbyopes when the words with 0.4° of character size were presented at the 35-cm viewing distance [10 % contrast, $F(1, 168) = 181.99$, $p < .001$, $\eta^2 = .102$; 100 % contrast, $F(1, 168) = 4.39$, $p = .038$, $\eta^2 = .003$]. Viewing distance affected both presbyopes' and nonpresbyopes' reading performance when the words were presented with 10 % contrast and 0.4° in character size [presbyopes, $F(1, 84) = 264.06$, $p < .001$, $\eta^2 = .121$; nonpresbyopes, $F(1, 84) = 11.14$, $p = .001$, $\eta^2 = .005$]: Reading was harder at the 35-cm viewing distance than at 70 cm. The effect of contrast was also observed for both presbyopes and nonpresbyopes when the words consisting of 0.4° characters were presented at 35 cm of viewing distance: Words with lower contrast required more time to read than those with higher contrast [presbyopes, $F(1, 84) = 264.06$, $p < .001$, $\eta^2 = .121$; nonpresbyopes, $F(1, 84) = 11.14$, $p < .001$, $\eta^2 = .005$]. For the presbyopes, the words written in smaller characters were harder to read than those in larger characters for all of the conditions except when the words with 100 % contrast were presented at 70 cm [$Fs(1, 84) > 4.11$, $ps < .046$]. For the

nonpresbyopes, on the other hand, this character size effect was observed only when the words with 10 % contrast were presented at 35 cm [$F(1, 84) = 22.86$, $p < .001$, $\eta^2 = .010$]. Thus, whereas there were clear differences between the presbyopes and nonpresbyopes for the 35-cm viewing condition, the presbyopes could read as quickly as nonpresbyopes in the 70-cm viewing condition, even when the words were presented at 0.4° in character size and 10 % contrast. It should be noted that, even for the 35-cm viewing distance, the presbyopes' reading performance reached almost the same level as that of the nonpresbyopes when the character size was large.

## Experiment 2

In Experiment 1, we investigated the effects of viewing distance, contrast, and character size on reading for presbyopic and nonpresbyopic participants by using three-character hiragana words. We found that reading performance for the presbyopes was far worse than that for the nonpresbyopes when words with 10 % contrast and 0.4° of character size were presented at a viewing distance of 35 cm. The results also showed that, even for the near viewing distance, the presbyopes' reading performance was improved by increasing the contrast (and/or the character size), making their reading performance near that of the nonpresbyopes, although a significant difference remained between the participant groups. Previous studies have demonstrated that reading performance for normal vision is little affected by a tenfold reduction in contrast from 100 % to 10 % and that it declines rapidly only when the contrast drops below 10 % and approaches the threshold for character recognition (typically between 1 % and 2 %; Legge et al., 1987; Rubin & Legge, 1989). For people with low vision, on the other hand, very high contrast

can help them read (Legge et al., 1987). Thus, in Experiment 2, we investigated in detail how contrast would affect presbyopes' reading performance for words presented at a viewing distance of 35 cm.

This experiment used words written in a mixture of kanji characters and hiragana (see Fig. 2) instead of only in hiragana, because most adult Japanese are more familiar with sentences written in a mixture of kanji and hiragana characters than with words written only in hiragana.

Method

*Participants* A group of eight presbyopes took part in our second experiment (50–59 years of age, with a median of 53.0; seven females and one male), along with eight non-presbyopic participants (22–31 years, median of 25.0; one female and seven males). Three of the presbyopes had also participated in Experiment 1. All of the presbyopes noted their presbyopic symptoms but did not report any other defects in vision. Table 4 shows the participants' ages, genders, and (corrected) visual acuity. The amplitude of accommodation for two of the presbyopes (participants N and P in Table 4) was not measured because they were unavailable for the measurement sessions with the ophthalmologists. For the remaining six presbyopes, the average amplitude of accommodation was 0.89, in the range from 0.1 to 1.42. The ophthalmologists diagnosed that these participants had presbyopia but no other identifiable

**Table 4** Eye condition/acuity of participants ($N = 16$) for Experiment 2

| Participant | Age | Sex | Acuity (3 m) | | |
|---|---|---|---|---|---|
| | | | L | R | Binocular |
| A | 23 | M | 1.0 | 1.2 | 1.5 |
| B | 23 | M | 0.3 | 1.5 | 1.5 |
| C | 24 | F | 1.0 | 1.0 | 1.0 |
| D | 28 | M | 1.0 | 0.9 | 1.2 |
| E | 24 | M | 1.2 | 1.2 | 1.5 |
| F | 31 | M | 1.2 | 1.2 | 1.5 |
| G | 22 | M | 0.6 | 0.8 | 0.8 |
| H | 25 | M | 1.2 | 1.2 | 1.5 |
| I | 50 | M | 1.0 | 0.8 | 1.2 |
| J | 53 | F | 0.7 | 0.7 | 0.9 |
| K | 59 | F | 0.9 | 0.9 | 1.2 |
| L | 54 | F | 0.3 | 1.0 | 1.0 |
| M | 50 | F | 0.6 | 0.6 | 0.8 |
| N | 50 | F | 0.6 | 0.8 | 0.9 |
| O | 54 | F | 0.8 | 0.8 | 1.0 |
| P | 54 | F | 0.5 | 0.6 | 0.9 |

"Acuity" is decimal acuity for distance vision, in which 20/20 is 1.0 and 20/40 is 0.5, and was measured with (myopia) corrections

**Table 5** Samples of Japanese words used in Experiment 2

| Word | Pronunciation | Word Class | Meaning |
|---|---|---|---|
| (a) | chi-ka-su-i | noun | groundwater |
| (b) | ya-sa-shi-i | adjective | kind |
| (c) | se-i-ji-ka | noun | politician |
| (d) | tsu-i-ya-su | verb | spend |
| (e) | mo-chi-i-ru | verb | use |
| (f) | ta-n-na-ru | adverb | mere |
| (g) | ji-do-u-shya | noun | automobile |
| (h) | ki-bi-shi-i | adjective | hard, strict |
| (i) | chi-he-i-se-n | noun | horizon |
| (j) | ka-zo-e-ru | verb | count |

The appearance of each word is shown in Fig. 2

pathology. While those who had myopia had it corrected with spectacles or contact lenses, presbyopic corrections were not allowed during the experiments. Even for the short-viewing-distance condition (35 cm), the presbyopes wore myopia-correcting lenses if needed. All were native Japanese speakers.

*Stimuli and procedure* The apparatus was the same one used in Experiment 1. All of the words used were written in a mixture of kanji and hiragana. The words were selected within the range of high word familiarity —that is, over 5.4 (maximum: 7) in the Japanese familiarity-controlled word lists (Amano & Kondo, 2003). Words containing katakana or demonstratives were excluded from the candidates. Thus, in each trial, test words were chosen randomly from a pool of 2,249 words. The number of strokes in each kanji ranged from 2 to 22 (Fig. 3 and Table 5 show examples). The words were rendered in MS Gothic in black on a white background 121.0 or 122.7 cd/m² in luminance. The character size was constant at 0.4°, and the viewing distance was also constant at 35 cm.

The procedure was identical to that in Experiment 1, except for the following changes. Reading performance was measured with various contrast values of the words. For the nonpresbyopic participants, 10 %, 12 %, 15 %, 20 %, 25 %, 30 %, and 100 % contrast were tested. For the presbyopic participants, 25 %, 30 %, 35 %, 40 %, 50 %, 70 %, and 100 % contrast were tested. These contrast values were determined in preliminary experiments. Each contrast was tested in a different session, and the order of the tested contrast values was randomized.

Results and discussion

Figure 4 shows the average thresholds of exposure duration obtained in Experiment 2 as a function of the contrast of the

tested words (filled and open circles). Figure 4 also includes the results of Experiment 1 for comparison (filled and open triangles). The data for two participants in the presbyopic group (K and P in Table 4) were removed from the subsequent analyses because they failed to read the words at all in some of the contrast conditions tested. As is described in the Method section, the measured amplitudes of accommodation were not available for two presbyopes. While the data of one of them (P in Table 4) were removed for the aforementioned reason, those of the other (N in Table 4) were included in the subsequent analyses because her performance was consistent with that of the other presbyopes.

For both groups, as contrast was increased, the thresholds of the exposure duration rapidly dropped by evenly spaced amounts at first, and then decreased more gradually with further contrast increases. The thresholds of the exposure duration were analyzed in a one-way ANOVA for each group. The main effect of contrast was observed for both groups [presbyopes, $F(6, 30) = 3.57$, $p = .009$, $\eta^2 = .300$; nonpresbyopes, $F(6, 42) = 46.36$, $p < .001$, $\eta^2 = .758$]. The post-hoc tests (Tukey's HSD, $\alpha < .05$) revealed significant differences between the 25 % and >50 % contrast conditions for the presbyopes. For the nonpresbyopes, on the other hand, there were significant differences between 10 % and the higher contrasts, 12 % and the higher contrasts except for 15 %, and 15 % and the higher contrasts except for 20 %. The same ANOVA was also performed after normalizing each

participant's data at the various contrast levels to the data at 100 % contrast. A main effect of contrast was observed for both groups [presbyopes, $F(6, 30) = 4.49$, $p = .002$, $\eta^2 = .298$; nonpresbyopes, $F(6, 42) = 19.55$, $p < .001$, $\eta^2 = .627$]. Post-hoc tests (Tukey's HSD, $\alpha < .05$) revealed significant differences between the 25 % and >40 % contrast conditions for the presbyopes. For the nonpresbyopes, on the other hand, we found significant differences between 10 % and the higher contrasts, 12 % and the higher contrasts except for 15 %, and the 15 % and 100 % contrasts. These analyses showed that the reading performance of the nonpresbyopic participants was more sensitive to the current contrast variations than was that of the presbyopic participants. Large interparticipant variability for the presbyopes likely contributed to their relatively small effects of contrast. For example, the threshold exposure durations for the presbyopes ranged from 471 to 3,981 ms for 25 % contrast, giving a difference of 3,510 ms. The minimum interparticipant difference was 604 ms, for the 50 %-contrast condition. For the nonpresbyopes, on the other hand, the largest interparticipant difference was just 427 ms, obtained for the 10 %-contrast condition.

Next, we calculated minimum exposure duration and the critical contrast. The minimum exposure durations were given for the 100 %-contrast conditions in both groups. The duration was significantly larger for the presbyopes (430 ms/word) than for the nonpresbyopes (134 ms/word) [$t(5) = 3.43$, $p = .018$, $r = .549$, Welch $t$ test]. We defined the contrast that would double the minimum exposure duration by modifying Rubin and Legge's (1989) definition, which was based on reading speed data\. The contrast values were estimated by an interpolation or extrapolation method using the two contrasts nearest twice the minimum exposure duration. Unfortunately, we could not obtain this critical contrast for one of the presbyopes. The average critical contrasts were 36.0 % for the presbyopes and 16.4 % for the nonpresbyopes, and they were significantly different from each other [$t(4) = 4.21$, $p = .022$, $r = .652$, Welch $t$ test].

Figure 4 also shows the data obtained in Experiment 1, in which words written only in hiragana were used. Most adult Japanese are more familiar with sentences written in a mixture of kanji and hiragana characters, like the words used in Experiment 2, than with those written only in hiragana. Therefore, if familiarity had any effects on reading, reading performance should have been improved in Experiment 2 as compared with that in Experiment 1. On the other hand, kanji characters look complicated and contain more components of high spatial frequency than do hiragana characters. This implies that reading performance should have deteriorated in Experiment 2 as compared with Experiment 1 (Legge et al., 1985). Three conditions were comparable between Experiments 1 and 2: 100 % contrast for the presbyopes, and 10 % and 100 % contrast
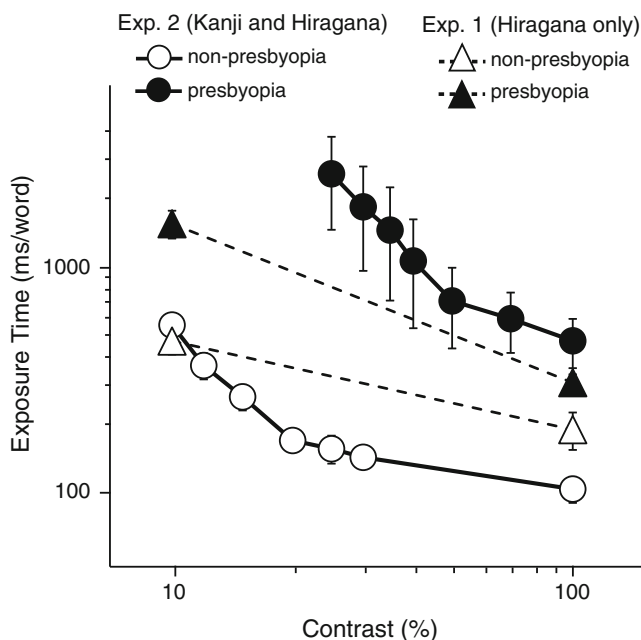


Fig. 4 Thresholds of exposure duration (ms/word) as a function of luminance contrast. The open and filled circles indicate the exposure durations for the nonpresbyopes ($N = 8$) and presbyopes ($N = 6$), respectively, in Experiment 2. The open and filled triangles indicate the corresponding values from Experiment 1. Error bars denote the standard errors of the means

for the nonpresbyopes. Performing Student's or Welch's *t* tests for these conditions, we found a significant difference for the 100 %-contrast condition for the nonpresbyopes, $t(15) = 2.14$, $p = .049$, $r = .140$: The words written in a mixture of kanji and hiragana were easier to read than those only in hiragana when their contrast was 100 %. This may be because the contrast was high enough to cancel out the effect of the high-spatial-frequency components contained in kanji on reading, so that the effect of familiarity became salient. In contrast, there were no significant differences for the other conditions: 100 % contrast for presbyopes, $t(6) = 0.86$, $p = .421$, $r = .145$, and 10 % contrast for the nonpresbyopes, $t(18) = 1.02$, $p = .323$, $r = .056$. The effects of familiarity and high-spatial-frequency components might have counteracted each other.

In order to compare with the data previously reported by Legge et al. (1987), which showed the effect of contrast on reading English for normal vision, we also calculated reading speeds according to the following equation:

Readingspeed(words/min)

$$= 60,000/\text{RSVP word exposure duration(ms)}.$$

The maximum reading speeds were obtained at 100 % contrast for both groups; these were 499 words/min for the nonpresbyopes and 168 words/min for the presbyopes. The maximum reading speed for the nonpresbyopes was one and a half times as large as that for that reported by Legge et al. (1987), which was about 350 words/min at a contrast of 96 % for character sizes from 0.25° to 2.0°. Furthermore, rapid declines for reading speed were observed when the contrast was below 25 % for the nonpresbyopes and below 50 % for the presbyopes: The declines for the presbyopes were about 30 % from 100 % to 50 % contrast and 50 % from 50 % to 25 % contrast. For the nonpresbyopes, the declines were about 30 % from 100 % to 25 % contrast and 70 % from 25 % to 10 % contrast. This is inconsistent with previous studies, which showed that reading performance for normal vision was little affected by a tenfold reduction from 100 % to 10 % contrast (Legge et al., 1987; Rubin & Legge, 1989). These inconsistencies might be due to differences in the measurement methods (the drifting-text method for the previous studies vs. RSVP for the present study). Legge and Bigelow (2011) reported that RSVP reading speeds were typically much higher than speeds for static or drifting text (see Fig. 2 in Legge & Bigelow, 2011). For example, Legge et al. (1985) showed a maximum reading speed of about 250 words/min for drifting text with over 94 % contrast, while Legge et al. (2007) reported about 1,000 words/min for RSVP text with 90 % contrast. Other factors that could affect reading performance are differences in the text materials (sentences in the previous studies vs. a sequence of three-character isolated words in ours) and

language (English vs. Japanese). The effects of these factors should be investigated in future studies.

## General discussion

In the present study, we measured presbyopes' reading ability by using the RSVP paradigm and compared their performance with that for nonpresbyopes. The results of Experiment 1 showed that the reading performance for the presbyopes was far worse than that for the nonpresbyopes when words with 10 % contrast and 0.4° character size were presented at 35 cm of viewing distance. Experiment 2 revealed the effect of contrast on reading performance for the near-viewing condition (35 cm). For both groups, reading performance was improved with an increase in contrast, although the effect of contrast on reading for the presbyopes showed larger interparticipant variability than did the effect for the nonpresbyopes. The minimum exposure duration for the presbyopes was over three times as long as that for the nonpresbyopes. Additionally, the critical contrast for the presbyopes (36.0 %) was considerably higher than that for the nonpresbyopes (16.4 %).

Thus far, little is known about age-related declines in reading ability, while many other visual abilities have been reported to be degraded (Betts et al., 2007; Daneman & Carpenter, 1980; Derefeldt et al., 1979; Faubert, 2002; Faubert & Overbury, 2000; Fiorentini, Porciatti, Morrone, & Burr, 1996; Johnson & Marshall, 1995; Owsley et al., 1983; Rayner & Inhoff, 1981; Sekuler & Sekuler, 2000; Trick & Silverman, 1991; Wood & Bullimore, 1995; Wright & Drasdo, 1985). For example, Akutsu et al. (1991) found that elderly participants who did not suffer from eye disease (60–74 years of age) read as fast as young participants for character sizes ranging from 0.3° to 1.0°. Yu et al. (2010) reported that training to enlarge visual span could improve reading speeds for older adults as much as it did for young people, although several minor differences could be observed between the young and older groups. In contrast, the present study demonstrated that reading performance among the middle-aged was clearly degraded for the near-viewing condition (35 cm). A major difference between these studies and ours was our focus on the age-related decline in accommodation. In Akutsu et al., participants' declines in accommodation were corrected by lenses. As we get older, optical functions other than accommodation also degrade. For example, pupil size becomes smaller (Hennelly et al., 1998; Loewenfeld, 1979), the density of the crystalline lens increases (Pokorny et al., 1987; Said & Weale, 1959; Weale, 1961), and intraocular light scatter and optical aberrations also increase (Artal et al., 2003; Glasser & Campbell, 1998). In the present study, in order to single out the effect of declines in accommodation on reading, we

targeted middle-aged adults (47–59 years of age). Consequently, the results suggest that decreases in reading performance accompany declines in accommodation. Furthermore, we used the RSVP paradigm, so that our results could not be accounted for by declines in eye movements (Sharpe & Sylvester, 1978; Spooner et al., 1980).

The reduction of accommodative power generally makes it difficult to focus on near objects. The present study clearly showed that presbyopes' reading was severely impaired (1,433 ms) when small words with low contrast were presented at 35 cm of viewing distance, as compared with when words of the same size and contrast were presented at 70 cm of viewing distance (396 ms). The threshold increased more than threefold just by shortening the viewing distance. It is true that viewing distance affected reading performance for the nonpresbyopes, as well (483 ms at 35 cm vs. 270 ms at 70 cm); however, the threshold for 35-cm viewing did not exceed more than double the threshold for 70-cm viewing. These results demonstrate the strong influence of accommodative power on reading at a near viewing distance. Future work will need to clarify what aspect of declines in accommodation affects reading performance (see, e.g., Mordi & Ciuffreda, 2004). To this end, we should measure the actual accommodation achieved in each participant for each accommodation demand and the ability to sustain peak accommodation. Additionally, relationships between declined accommodation and decreased retinal illuminance and between declined accommodation and contrast sensitivity should also be clarified.

Another important point is that an increase in contrast can improve reading performance at a viewing distance of 35 cm. By increasing the contrast from 10 % to 100 % in Experiment 1, and from 25 % to 100 % in Experiment 2, the threshold exposure durations dropped by about one-fourth. Thus, our results provide psychophysical evidence for strong interactions in presbyopes' reading between viewing distance and luminance contrast. This would be useful in the development of clinical tests for presbyopia and in the design of presbyopes' reading aids.

In addition to age-related changes in the optics of the eyes, many studies have demonstrated declines in visual function linked to changes in cortical mechanisms (Betts et al., 2007; Daneman & Carpenter, 1980; Derefeldt et al., 1979; Faubert, 2002; Faubert & Overbury, 2000; Fiorentini et al., 1996; Johnson & Marshall, 1995; Owsley et al., 1983; Rayner & Inhoff, 1981; Sekuler & Sekuler, 2000; Trick & Silverman, 1991; Wood & Bullimore, 1995; Wright & Drasdo, 1985). One theory suggests that age-related changes in visual function are more pronounced in functions requiring complex and multiple stages of processing (Bennett, Sekuler, McIntosh, & Della-Maggiore, 2001; Faubert, 2002; Habak & Faubert, 2000). Obviously, reading requires

multiple stages of processing, from edge detection to character identification. Therefore, it would be likely that several age-related changes (not only declines, but also improvements) could be observed in reading. In fact, a few studies have shown an age-related decline in reading (Akutsu et al., 1991; Yu et al., 2010), although the effect has been less pronounced than those shown in other areas of visual performance. A recent study, on the other hand, reported that reading performance and contrast sensitivity for presbyopes were improved by perceptual learning without changing the optical characteristics of their eyes (Polat et al., 2012). This suggests that declines in the optical system can be to some extent independent of those in the perceptual system. In any case, future work should increasingly take the aging of both the perceptual and the optical systems into account in order to elucidate the mechanisms of age-related changes in reading.

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