

Silent reading as determined by age and visual acuity

Dieuwke H. A. Aberson and Don G. Bouwhuis

Institute for Perception Research, Netherlands

ABSTRACT

In this study silent reading by adults ranging in age from 35 to 90 years was investigated. The texts to be read were printed in black on white paper with character sizes varying from 1–9 mm x-height (visual angle 0.19° to 1.67°). In order to separate age effects from visual-acuity effects, subjects with different levels of visual acuity (0.1–2.5 decimal acuity) participated in the experiment. Silent reading rate was employed as the dependent variable. Visual acuity affected reading rate most, followed by letter size. In normal-acuity subjects the variance in reading rates decreased as a function of age. Reading rates initially increased rapidly with increasing letter size, but after reaching an optimum gradually declined again as letters became larger. For the different acuity classes there appeared to be clearly optimal letter sizes, varying from 1.9 for the highest acuity group to 6 mm for the lowest acuity group at the 33 cm reading distance employed. However, the optimal reading rates of visually impaired subjects found in this study remained below those of individuals with normal acuity. This suggests that visual impairment is a more general neural phenomenon rather than merely a deficient optical image. The obtained reading-rate data could be accurately described by a theoretical model encompassing a decoding process and an integration process. It appeared that the model predictions were entirely determined by the smallest letter size at which reading is just possible with a specified visual acuity. It is concluded that both decoding and integration are dependent on visual acuity and that, in the absence of specific visual defects, ageing effects in reading can be completely explained by gradual lowering of visual acuity having its origin in central mechanisms.

RÉSUMÉ

La lecture silencieuse en fonction de l'âge et de l'acuité visuelle

On a examiné dans cette étude la lecture silencieuse d'adultes âgés de 35 à 90 ans. On a utilisé quatre groupes d'âge: 36–46 ans, 56–66 ans, 66–76 ans et plus de 76 ans

(le groupe d'âge 46–56 est absent de propos délibéré). De façon à dissocier les effets de l'âge de ceux de la diminution d'acuité visuelle, les groupes avaient une acuité normale (0.8), réduite (0.4–0.8) et faible (0.1–0.4). On a contrôlé également la taille des caractères: de 1 à 9 millimètres de hauteur. Les sujets ont lu 12 textes différents, constitués d'histoires courtes et distrayantes du même auteur (534 mots en moyenne). On a utilisé deux textes ayant une bonne qualité d'impression par taille de caractère. La vitesse de lecture a été mesurée en mots par minute. L'effet de l'âge sur la vitesse de lecture n'est pas significatif. La variance de la vitesse de lecture pour les sujets ayant une acuité normale diminue quand l'âge augmente, surtout du fait de l'absence de très bonnes vitesses de lecture chez les sujets plus âgés. La vitesse de lecture du groupe le plus âgé ayant une acuité normale est beaucoup plus basse que celle des autres groupes d'âge et ne varie pas beaucoup selon la taille des caractères, ce qui suggère un traitement central plus lent plutôt qu'une dégradation optique. L'acuité visuelle de ceux qui ont une bonne vue covarie avec l'âge: 1.8 en moyenne pour les 40 ans et 1.1 pour les plus de 75 ans. Les sujets âgés ayant une mauvaise acuité visuelle ont arrêté leur lecture plus souvent que les sujets plus jeunes ayant une mauvaise vision. Au dessous d'une vitesse de lecture silencieuse de 20 mots par minute ils n'étaient plus en mesure de comprendre ce qu'ils avaient lu. Il est probable que l'effort cognitif que demande le déchiffrage conduise à des temps de latence qui empêchent les processus mnémoniques de réaliser une intégration satisfaisante.

La vitesse de lecture est surtout fonction de l'acuité visuelle. La vitesse de lecture des sujets ayant les plus mauvais niveaux d'acuité visuelle est plus faible et ne peut pas être compensée de façon satisfaisante par l'utilisation de plus grands caractères. Il y a une interaction significative entre l'acuité visuelle et la taille des caractères: la taille optimale des caractères pour les vitesses maximales de lecture est plus élevée pour les sujets ayant un faible niveau d'acuité visuelle. Il apparaît que la taille optimale des caractères est nettement différente selon le niveau d'acuité visuelle du groupe: de 1.9 mm pour le groupe ayant l'acuité visuelle la plus élevée à 6 mm pour le groupe ayant l'acuité visuelle la plus faible. Néanmoins la vitesse de lecture est plus basse quand l'acuité visuelle est moins bonne. On peut décrire de manière précise les résultats obtenus relatifs à la vitesse de lecture avec un modèle théorique comportant un processus de décodage et un processus d'intégration. Il est apparu que les prédictions du modèle sont entièrement déterminées par la taille des lettres les plus petites pour laquelle la lecture est juste possible à un niveau d'acuité visuelle donné. On en conclue que le décodage et l'intégration dépendent tous deux de l'acuité visuelle et que, en l'absence de difficultés visuelles spécifiques, on peut expliquer en totalité les effets de l'âge sur la lecture par une diminution progressive de l'acuité visuelle d'origine centrale. Dans le modèle courant on explique une difficulté plus grande avec de plus grands caractères par l'effort nécessaire pour parvenir à intégrer des patrons visuels pour des plages plus grandes.

INTRODUCTION

In order to keep informed, people depend to a considerable extent on reading material, especially when they live in a situation of relative isolation. This is often the case for elderly people who participate less actively in society. While there may

be an increased need for reading in old age, reading itself may become more difficult due to the potential perceptual and cognitive decline. Though general features of visual decline as a function of advanced age are well documented (Spear, 1993; Weale, 1986), it is not well known how these actually interact with the reading process. Systematic research on the visual reading process in old age is practically non-existent. Usually, it is implicitly assumed that the effects of age are similar to those of low vision. Legge and his associates have systematically explored the consequences of low vision ('normal vision' in their terms) on the reading process (Legge, Pelli, Rubin and Schleske, 1985; Legge and Rubin, 1986). However, whether the ageing visual system will exhibit exactly the same phenomena as low vision is unclear. Furthermore, the low vision Legge and his associates have studied (Legge, Rubin, Pelli and Schleske, 1985) is much more severe than the reduced and low levels of visual acuity considered here. In the current study, therefore, ageing effects on reading performance will be considered independently of effects of visual acuity.

According to Bouma (1978) reading is considered to be composed of four different processes: (1) forming an optical image of the fixated text part on the retina; (2) recognizing the fixated words; (3) moving of the eyes to the next fixation point; and, finally, (4) integration of information across eye fixations. These aspects are discussed below, with particular respect to the influence of advancing age.

1. *Optical image*

When the text is of high graphical quality and the visual acuity of the fixating reader is adequate, the optical image will have sufficient detail to make fluent reading possible. As the optical system ages, retinal illumination diminishes as a result of senile miosis, and increased lenticular light absorption (Elliott, Whitaker, McVeigh, 1990). Lenticular light scatter increases due to particles in the eye fluid, and reduced transparency of the lens. The accommodative amplitude decreases as a result of changes in shape due to changes in the mechanical properties of the capsule and matrix. Also, the percentage of people suffering from eye pathologies, such as cataract, glaucoma, macular degeneration or retinopathy due to diabetes mellitus is increased for older groups (Gittings and Fozard, 1986; Sloane and Kraut, 1975; Fozard *et al.*, 1977). All of these would lower the quality of the optical image. Pitts (1982) estimates that 30% of people over 75 are visually handicapped.

Reduced retinal illumination can be countered by higher illumination. However, too high levels of illumination may lead to glare, especially due to increased light scatter within the eye. Old people have a much lower tolerance to glare (Pulling, Wolf, Sturgis, Vaillancourt and Dolliver, 1980). High illumination levels also lead to pupil constriction, counterproductive on the one hand, but on the other hand improving depth of field (Sloane, Owsley and Alvarez, 1988). Solutions for improved imaging with lenticular and retinal pathologies are generally less obvious; optical aids (magnification of the material) usually reduce the size of the visual field (Pelli, Legge and Schleske, 1985; Pelli, 1992).

2. *Word recognition*

One of the consequences of an inferior optical image could be that the poorer quality of sensory information increases the time needed for encoding the textual material

into words, leading to a lower reading rate. Apart from the reduced reading rate, reading errors may occur, which, in turn, may result in even slower reading. Myerson *et al.* (1990) established that the better the optical image, the more information is acquired and the faster and more accurate its recognition will be. However, it must be remembered that the optical image is only the input for the process of word recognition. Beside letter perception, word knowledge is also important for word recognition (Bouwhuis and Bouma, 1979). Word knowledge, in particular, improves with experience (Anstey, Stankow and Lord, 1993) and so with age this may be assumed to offset limited visual degradation to some extent. The use of context may also be expected to profit from increased experience with age and to assist the reading process. Nevertheless, encoding time would be expected to be somewhat longer for older people, due to a generally observed slowing-down with age, both visually and cognitively.

3. *Eye-movement control*

Bouma and de Voogd (1974) concluded from their experiment using a line-stepper that programming horizontal eye saccades is a fairly autonomous process. Reading proved to be possible without pre-information for the next retinal image. But, if present, parafoveal information (outside a visual angle of 1–2 degrees around the fixation point) will be used to send the eyes onto the next fixation. Evidence of the importance of parafoveal right field information for eye movement control in fluent reading is presented in several studies (Rayner *et al.*, 1982; McConkie and Rayner, 1975, 1976; Lima and Inhoff, 1985; Blanchard, Pollatsek and Rayner, 1989; Inhoff, 1989; Morris, Rayner and Pollatsek, 1990). So, reduced parafoveal visibility, due to poor levels of visual acuity, could make eye control less effective, resulting in a lower reading rate. In smooth pursuit tasks it was found by Sharpe and Sylvester (1978) that the latency, velocity and accuracy were affected by increasing age, but that for small saccades ($< 20^\circ$, within the limits of a visual field for which visual acuity is not affected by age) velocity of young and old subjects did not differ, nor did accuracy (Warabi, Kase and Kato, 1984). This leaves only longer saccade latencies for older subjects (Sharpe and Zackon, 1987), which would lead to longer fixation durations.

Eye movement control largely proceeds in an autonomous fashion even when intermittent support by top-down processes is available. This causes the eye fixation to land mostly on the relevant words, but it will also occasionally happen that the eye moves on before the fixated word has been recognized. So, corrective (top-down) regressive saccades will occur. Other factors affecting eye-movement control could have been introduced by corrective lenses, prescribed without taking into account any binocular vision anomalies. This could result in history and symptoms like horizontal and vertical diplopia, jumbling of print, asthenopia, intermittent blurring and print being too small (Rundström and Eperjesi, 1995).

4. *Integration over fixations*

Finally, all (partly overlapping) text parts have to be integrated into a sentence. Concerning this integration process different assumptions are made by different authors. Bouma *et al.* (1974) propose that pieces of text information acquired from

several successive eye fixations are internally buffered before being semantically processed. Rayner, McConkie and Zola (1980) found support for integration facilitation by preliminary letter identification (two letters of the word in the parafovea) in a buffer, but not on the basis of their visual characteristics as McConkie and Rayner (1976) and Rayner (1978) suggested. Just and Carpenter (1980) argued that readers interpret a word while they are fixating it, and continue to fixate it until they have processed it as far as they can and the remaining within-sentence ambiguities are dealt with at the end of a sentence.

Various memory stores are assumed to be operative during reading. Ageing effects observed in these systems have been described comprehensively by Craik and Bosman (1992). First, it appears that there is essentially neither loss nor gain in sensory memory (or iconic memory) with age. In short-term memory Craik *et al.* (1992) distinguish *primary memory*, in which material is kept unchanged for brief periods, and *working memory*, in which material is transformed actively while it is being held. Unlike working memory, primary memory shows only a slight ageing loss. Since primary memory is supposed to be relevant for the integration process, this stage in reading is not likely to be much affected by ageing effects on memory. However, the process of integration will suffer as reading rates will become too slow, because information in short-term memory is available only for a short period. With markedly reduced reading rates information will be lost before the end of the sentence has been reached.

Another memory system directly relevant for reading is semantic memory, including vocabulary, factual knowledge and names. Both vocabulary and factual knowledge show gradual increases during ageing, at least up to 70 years, while memory for names shows significant losses. In respect of the use of context cues Cohen and Faulkner (1983) found in their study on context facilitation that the older participants were superior to younger ones when context gave rise to more than one alternative, whereas their performance was equal in more constraining contexts. These phenomena suggest that word recognition and integration in reading will not be affected by ageing, and may even exhibit some gains with age.

Reading performance of elderly people

In spite of the various types of deterioration associated with old age, accuracy of performance does not have to be affected, because that is primarily determined by the effectiveness of compensation for the diminished capacities by experience with the task (Salthouse and Somberg, 1982; Dixon and Bäckman, 1993). Also, elderly readers usually try to attain high accuracy at the expense of time expenditure. Consequently, older subjects read aloud somewhat more slowly than younger ones, with comparable visual acuity levels (Bouma *et al.*, 1982). Elderly people describe their diminished reading capacity in terms of fatigue and lack of concentration (Legein and Bouma, 1982). However, reduced levels of visual acuity tend to impair reading much more than old age *per se*. As visual acuity decreases, on average, with age (Weale, 1963), reading difficulties may be expected to occur in the course of life. Greenberg and Branch (1982) maintained that roughly 5% of persons over 65 have visual impairment severe enough to prevent them from reading newspaper print even with corrective spectacles.

Visual acuity decreases in old age. Consequently, with appropriate correction and regardless of pathology (Spear, 1993; Gittings *et al.*, 1986; Owsley, Sekuler and Siemsen, 1983), and assuming that word recognition efficiency of poor acuity readers improves for larger characters, it is normally expected that the use of larger characters will result in higher reading rates. This expectation holds, as Rayner (1978) states, if the reading process *in itself* is not affected by the use of larger characters. Rayner (1978) argues that enlarging print, in addition to causing letters to occupy a greater visual angle, also makes it possible for the reader to identify letters further from the fixation point. In fact, reading rates of subjects with poor acuity improved slightly for larger characters in the study by Bouma *et al.* (1982). However, these higher reading rates did not attain the reading rates of normal acuity subjects. The character sizes employed in their study ranged from 1 to 16 mm, the height of characters being expressed as the size of the lower-case letter h (h-height) in mm, presented at a viewing distance of 33 cm. They did not expect reading rates to improve further for very large letters but, instead, to find a ceiling effect because oral reading rate was measured. This probably concealed the effects caused by very large characters. In addition, they studied word recognition with the same letter-size variation. Words were presented at a distance of four letters to the left of the fixation point, centred on the fixation point, or presented four letters to the right. For subjects with normal acuity for parafoveal right recognition an optimal character size of 3.2 mm h-height (= 2.3 mm x-height) was found, but one of 9 mm h-height (= 6.5 mm x-height) for poor acuity subjects, while for larger character sizes performance decreased again steeply. Interestingly, the slopes of the decrease coincided almost exactly for the normal and poor acuity subjects. Obviously, letter size sets a limit to word recognition from a certain point onwards, at least in the parafoveal field. This is in agreement with the following results, indicating that reading rates do not continue to improve with larger character sizes. Tinker (1958) studied the effect of type size on reading rate for a line width of 8 cm. He found an 11-point size (approx. 2 mm x-height) to be optimal, closely followed by 12 (approx. 2.2 mm x-height) and 10-point (approx. 1.9 mm x-height). On the basis of eye-movement studies he supposed that lower reading rates for smaller characters were caused by decreased visibility, while lower reading rates for larger characters were due to an increased amount of printing area to be covered. Vanderplas and Vanderplas (1980) had elderly subjects read texts differing in type-size, leading and line width. They found medium-sized characters (8–14 points) to be optimal in terms of reading speed, slightly smaller sizes from 8–12 points for younger and slightly larger (12–14 points) for older subjects. Legge *et al.* (1985a) also found maximum reading rates for intermediate character sizes subtending 0.3 to 2 degrees of visual angle, which is equal to letters of 1.5 to 10 mm x-height observed at a distance of 33 cm as we used in the experiment to be described. Also, reading rates declined rapidly for letters smaller than 0.3 degrees and more gradually for characters larger than 2 degrees visual angle.

In this investigation we tried to answer the following questions:

1. What are the effects of age and visual acuity on the rate of silent reading?
2. What are the optimal character sizes for silent reading for older subjects?
3. To what extent does the use of larger character sizes compensate for lower visual acuity in silent reading?

METHOD

Subjects

The preselection of the subjects was done by telephone interviews. If people indicated that they read a lot and were prepared and able to participate in the experiment, they were paid a visit during which their visual acuity and IQ were determined. Visual acuity was expressed as decimal acuity determined by a Landolt-ring test, with the rings reduced in size (for a distance of 33 cm instead of the usual 5 metres). By using Landolt-rings instead of letter charts differences in legibility between the characters are avoided; this is in accordance with recommendations of Bailey and Lovie (1976). Subjects watched with both eyes from a 33 cm distance with their corrective spectacles. Subjects had to be highly motivated readers and to score about average on the shortened version of the *Groninger Intelligentie Test* (Snijders and Verhage 1962).

From about 250 people interviewed, 55 subjects were selected. These subjects had generally graduated from higher education and in some way eventually expected to benefit from results of this kind of investigation. For the reduced and poorly sighted groups, subjects had been initially recommended by an ophthalmologist, so we were informed about their medical data. Subjects were assigned to four age categories: 36–45 years, 56–65 years, 66–75 years and > 75 years. The age category of 46–55 years of age was left out on purpose, because previous research on reading and word recognition had revealed no difference between 40-, 50- and 60-year-olds (Bouma *et al.*, 1982). Nested within these age categories were three visual acuity groups: normal acuity (≥ 0.8), reduced acuity (0.4–0.8) and poor acuity (0.1–0.4). It was difficult to find subjects with poor acuity having undamaged fields of vision. Only two subjects (with glaucoma) could be found for the 36–45 years group, but they declined to participate. So, in this age category the reduced acuity group was absent. Furthermore, it was difficult to find old people who were frequent readers and were healthy enough to participate. In the end, eleven age/visual acuity groups were obtained consisting of five subjects each. Table 1 gives an overview of the conditions and IQ scores.

Table 1. Average IQ-measures (standard deviations in parentheses) of the experimental groups. Each cell comprises five subjects.

	Age categories			
	36–45 years	56–65 years	66–75 years	> 75 years
Poor visual acuity (0.1–0.4)	95.2 (6.5)	106.4 (8.5)	91 (16.5)	92.4 (10.7)
Reduced visual acuity (0.4–0.8)	— —	105.8 (13.3)	99.8 (17.1)	84.6 (17.3)
Normal visual acuity (≥ 0.8)	106.2 (10.1)	115.4 (9)	119 (4.2)	116.2 (6)

The visual acuity categories were chosen according to distinctions that are easy to make in practice. The group with visual acuity levels of 0.8 and higher did not have any difficulty with reading whatsoever. The group with visual acuity levels from 0.4 to 0.8 had no difficulty with reading normal-sized characters, under conditions of proper contrast and illumination levels. The group with visual acuity levels from 0.1 to 0.4 needed some kind of magnification in addition to proper contrast and illumination levels. Each group comprised both men and women. There were more women than men (3 to 2) in each experimental group except in the 56–65-year-old group with reduced acuity (4 to 1).

In spite of all selection efforts some differences remained between the experimental groups. Among the normal acuity subjects visual acuity varied from 0.8 to 2.5. Average visual acuity decreased somewhat with age, from an average visual acuity of 1.8 for the 36–45 years group to 1.1 for the > 75 years group. The youngest poor acuity group (36–45 years) consisted of subjects with congenital vision defects, while the older groups had acquired poor vision with advancing age. Irrespective of the specific type of disease, subjects who participated were able to recognize words in the foveal area of the retina. Thus severe central defects of the retina such as foveal loss were avoided, as well as diseases of the optic nerve, but it was not possible to find only subjects with undamaged fields of vision. In the younger groups there were relatively more diabetics, all of whom had had laser treatment. A reduced perceptual field (measured with a perimeter by the resident ophthalmologist) was very common among the 70-year-olds with poor acuity. Among the five poor acuity 80-year-olds, four subjects saw primarily with one eye. Unfortunately IQ covaried with visual acuity. The correlation of visual acuity with IQ was significant ($r = 0.70$, $p > 0.02$). Considering the particular difficulty in composing the subject-groups this is in all likelihood due to a sampling effect. However, it is doubtful whether these differences in IQ resulted in any differences in reading rate at all, considering the fairly simple text content.

Materials and procedure

Silent reading rate was chosen as the dependent variable. The obvious reason for studying silent reading as opposed to reading aloud is that practically all our reading is silent. In another study where we registered eye movements (Aberson, in preparation) it was demonstrated that silent reading in adverse conditions does not deteriorate to rapid scanning for meaning. Reading aloud is much slower and introduces a ceiling related to pronunciation-speed (Bouma *et al.*, 1982) and still does not guarantee text-comprehension.

Subjects were allowed to use their own reading glasses and they read at the usual reading distance of about 33 cm. They were instructed to read as they customarily would. They were told they would be asked a question after each text to check whether they actually understood the content of the story. For the reading task 12 entertaining short stories, written by the same author, were selected. The texts had a similar style of writing and comparable lengths: an average of 534 words (s.d. = 103.34). This corresponded to one-and-a-half page stories in the original source. The Flesch-Douma score was derived from the formula given in Flesch (1951) and expresses the estimated reading difficulty level based on a number of formal properties of the texts: an average of 97 (s.d. = 3.67). A

Flesch-Douma score of 90 or higher refers to 'very easy' text, so all the texts were considered very easy.

The text pages with the different character sizes were produced in high-quality print on paper sheets measuring 50 cm (h.) \times 60 cm (w.). Six character sizes were used with 1, 1.5, 2.5, 3.8, 6 and 9 mm x-height. We chose lay-out characteristics so as to keep the line length/line height (character size and interlinear distance) ratio optimal, i.e. at least 19. Our interline spacing was clearly above the spacing for comparable character sizes which was required for a 'clear text' rating in a study by Wilkins and Nimmo-Smith (1987). The contrast ratio, measured by a Pritchard luminance meter, was 1 : 16. Each text was printed in proportional print in Helvetica-light type face, left-justified in lines of approximately 10 words each. The visual characteristics of the texts are summarised in Table 2. In order to maintain uniform letter and word spacing, texts were not right-justified, so that many lines were shorter than the maximal width indicated in Table 2.

Table 2. Visual characteristics of the texts used in the experiment.

[Letter sizes (x-height) in mm and in degrees of visual angle ($^{\circ}$), and degrees of visual angle ($^{\circ}$) subtended by the total text width, column width and column height.]

Text	x-height (mm)	Visual angle ($^{\circ}$)	Inter-line dist. (mm)	Text width ($^{\circ}$)	Column width ($^{\circ}$)	Column height ($^{\circ}$)
1 and 2	1.0	0.17	2.1	24.8	10.6	19.2
3 and 4	1.5	0.26	3	34.0	15.0	27.2
5 and 6	2.5	0.43	4.1	49.0	21.5	36.1
7 and 8	3.8	0.66	5.6	73.0	31.4	49.0
9 and 10	6.0	1.04	7.2	80.1	35.2	60.0
11 and 12	9.0	1.56	10.5	59.2	59.2	58.0

All texts in letter sizes up to 6 mm were printed in two columns of approximately equal height. Only the two 9 mm texts were printed in a single column, and required three consecutive sheets. During reading trials, these sheets lay on top of each other, and the top sheet was pulled away by the experimenter upon a finger signal from the reader. As the column width of texts with a letter size of up to 6 mm did not exceed 45° visual angle, no head movements would be necessary (cf the results of Sanders, 1963). The 9 mm texts with a column width of almost 60° visual angle would be read with maximal head movements of the order of 6° . As these are completely coordinated with eye movements (Sanders, 1963), they would not lead to longer reading times per se. Print-quality demands led to production costs that prevented having every text printed in all letter sizes. The texts were presented at an illumination level of 1600 lux in the centre, which decreased to 1000 lux at the edges from a fluorescent source. The well-adapted subjects read one practice text to get accustomed to the style of writing. After that, texts were read in the order from small print to large print and back to small print to compensate for potential effects of fatigue. During reading, the forehead was supported by a head rest to control reading distance, which was set at 33 cm. Although the texts were simple, a question was posed after having finished reading, in order to check whether the text was understood. Usually,

this was superfluous because subjects reacted with loud laughter while reading the text because of the amusing content of the stories. Not all subjects read all texts completely. There were two reasons. One reason was that subjects stopped after a few lines because they could not read the text with the smallest character size(s), at least to what they would call reading. The other reason was, that after reading 10 texts (or less), one of each character size and back to the text of 2.5 mm x-height, subjects, mostly the ones with poor visual acuity and of old age (in that order), refrained from reading a second text in that small letter size. So, all subjects participated in all conditions of character size, producing an actual reading speed of around 20 wpm if they stopped after a few lines or having their speed for a certain character size based on one text only. To avoid selective effects due to a single text, reading speeds were weighted proportionally on the basis of the results of a separate study intended to establish equal levels of text difficulty.

RESULTS

Text comprehension

Most questions asked after reading of every text were answered correctly indicating that the subjects were actually reading while being silent. Three questions, relating to text 9, 10 and 11 were suspected of being unreliable indicators of comprehension and were excluded from the analysis. On average, less than 10% of questions were answered incorrectly (see Table 3). Subjects who gave wrong answers were not of a particular age group, nor did they have a particular visual-acuity level.

Table 3. Percentages of erroneous responses to questions concerning the texts read.

	Texts											
	1	2	3	4	5	6	7	8	9	10	11	12
%	8	0	7	6	4	5	6	11	(23)	(36)	(30)	11

No questions were posed concerning texts that were not read because of fatigue or poor vision. This also applied to texts which subjects could only just read and where they had to concentrate so much on discerning the letters and words that they could not report the text content and thus stopped reading after a few lines. A positive correlation was found between text difficulty, expressed as the Flesch-Douma score, and the percentage of erroneous answers ($r = 0.70, p < 0.01$). More importantly: there was no significant correlation between the percentage of correct responses and the reading rate for the text ($r = 0.49, N.S.$).

Age

As the variances in the various samples were different, the conditions for a conventional ANOVA could not be met. Therefore, and also because of the missing

young group with reduced acuity, the reading rates were analysed by means of a MANOVA with repeated measures (subjects as replications) and with Age and Visual Acuity as between-subject factors and Letter Size as a within-subject factor for only one dependent variable (O'Brien and Kister Kaiser, 1975). The effect of Age was not significant ($F(3,44) = 2.12$; $p = 0.111$) and also the interaction between Age and Acuity failed to reach significance ($F < 1$). None of the pairwise differences between age groups was significant as a function of Letter Size, except for the 56–65 years group with reduced acuity, who read faster than the corresponding > 75 years group. The reading rate of the 56–65 years group was the highest on average. The lack of interaction is exemplified by Figure 1, showing the mean reading rates for the various character sizes of the normal-acuity > 75 years group and those of the other subjects with normal acuity. This Figure shows no interaction at all; the curves appear virtually parallel.

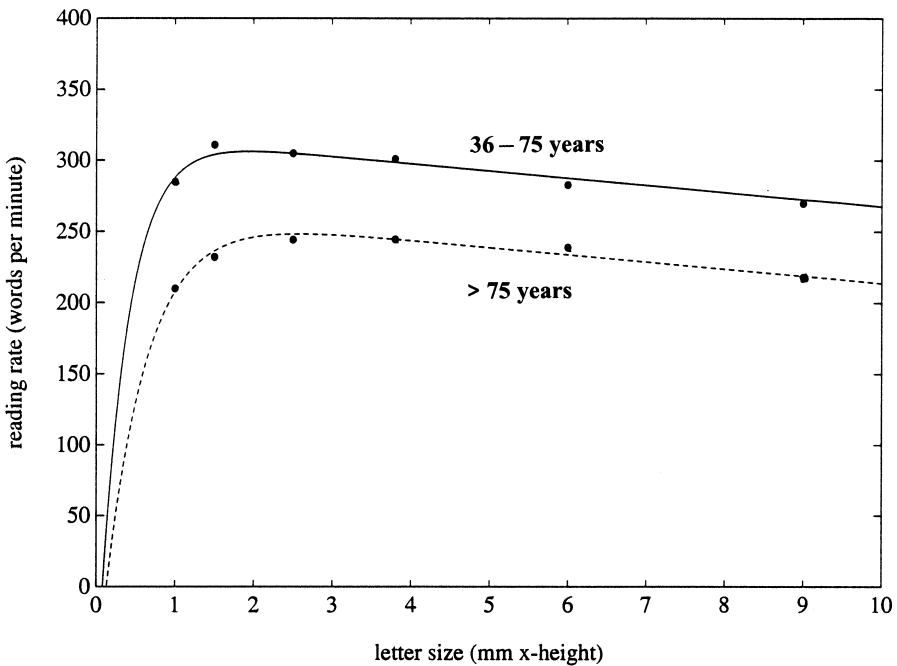


Figure 1. Silent reading rates of normal-acuity subjects as a function of letter size (in mm x-height) of the age group > 75 years compared with the other subjects (36–75 years). The curves represent theoretical predictions (see text).

Increasing age led to significantly decreasing amount of variance, analysed with Bartlett's test for homogeneity of variances ($B = 1.12$, $p < 0.0001$), because of the absence of extremely high reading rates amongst the older subjects. This effect of age is highly significant for normal sighted subjects ($B = 1.5$, $p < 0.0001$), still highly significant for subjects with reduced sight ($B = 1.55$, $p < 0.0001$), but not significant for the poor sighted ($B = 1.07$). Figures 2a, b and c show the individual mean reading

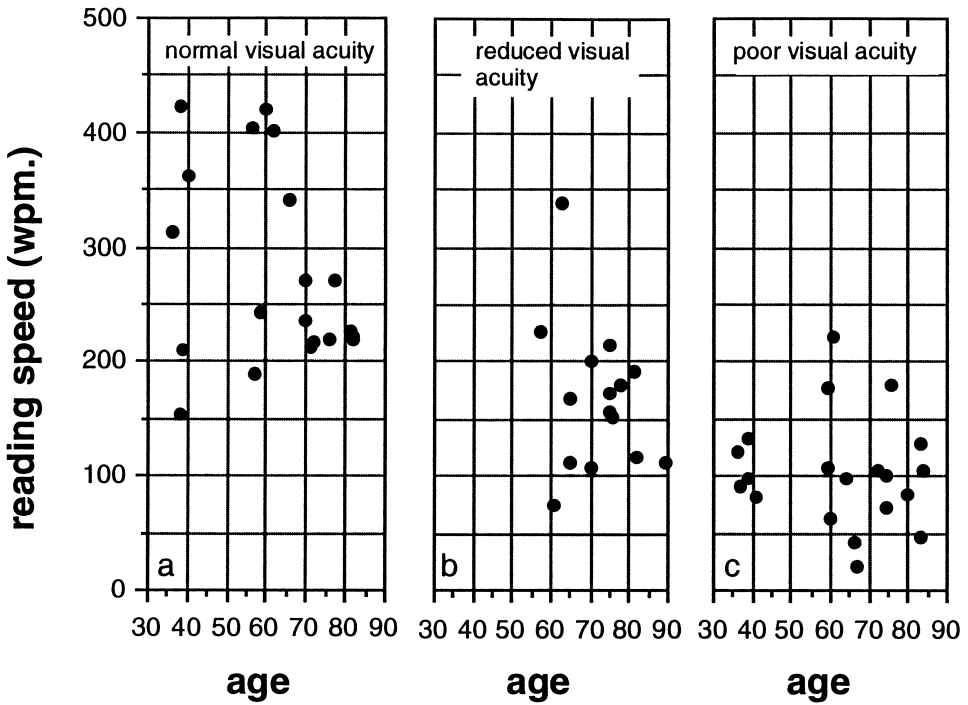


Figure 2. Silent reading rates of subjects with (a) normal-acuity, (b) reduced acuity and (c) poor acuity as a function of age.

rates of the normal-acuity, the reduced-acuity and the poor-acuity subjects, respectively, averaged over all character sizes.

Visual acuity and character size

The effect of Acuity was highly significant ($F(2, 44) = 34.2; p \leq 0.0001$). The effect of the within-subject variable Letter Size was also highly significant ($F(5, 40) = 11.6; p \leq 0.0001$). The interaction between Letter Size and Acuity was significant ($F(10, 80) = 2.83; p < 0.005$). Figure 3 shows the mean reading rates for the three visual acuity groups as a function of letter size. Averaged over texts the mean reading rate of subjects of all ages with normal visual acuity was 278 words per minute (s.d. = 88); that of subjects with reduced acuity was 169 (s.d. = 75); and that of the ones with poor acuity was 104 words per minute (s.d. = 71).

When IQ was employed as a covariate in a multiple analysis of covariance all of the above results were corroborated. Interactions of IQ with Age, with Acuity and with Age and Acuity were nonsignificant. The only noticeable effect of IQ was a slight rise in reading rate that was strongest for small letter sizes, but a multiple regression analysis showed that only visual acuity contributed significantly to the proportion of explained variance. The model with $r^2 = 0.86$ is $y = -56.44 + 108.23a - 0.09b + 1.6c$, where y = reading rate in wpm; a = visual acuity; b = age; and c = IQ.

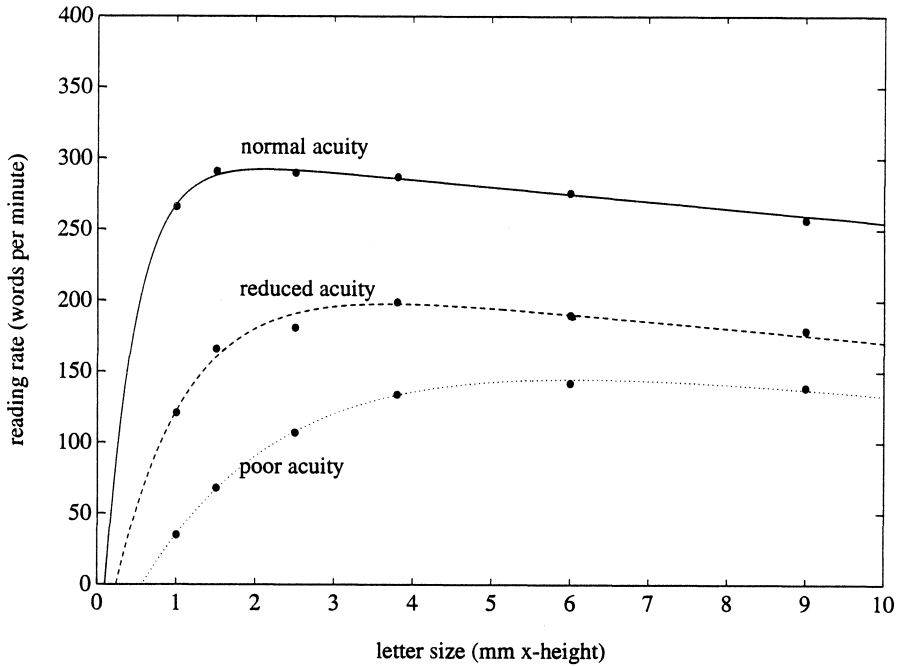


Figure 3. Silent reading rates as a function of letter size (in mm x-height) of normal acuity, reduced acuity and poor acuity groups. The curves represent theoretical predictions (see text).

A silent-reading-rate model

A model to describe reading rate in terms of (1) visual resolution (an exponential part) and (2) visual pattern integration (linear part) was formulated as follows:

$$r = (1 - e^{-\lambda(x - \mu)}) (a - 5x),$$

in which r is the reading rate in words/minute, λ is the rate of the exponential increase in reading rate with letter size, μ is the minimum letter size, below which reading is impossible with a given acuity, x is the letter size (expressed as mm x-height), a is the intercept and 5 the coefficient of the straight-line segment of the reading-rate curve.

It appeared that parameter λ could be derived from visual acuity and that λ was accurately described by $1/4\mu$. For μ values 0.1, 0.24 and 0.57 mm were employed for the normal, reduced and poor acuity groups, respectively (Figure 3), reflecting acuity levels of 1.45, 0.6 and 0.25; 0.08 and 0.13 mm were used for the 36–75 years groups and the > 75 years group respectively, corresponding to acuity levels of 1.8 and 1.1. The intercept a turned out to be an exact linear transformation of the rate parameter λ . Thus, effectively, there are no free parameters in this model. For the theoretical curves in Figure 3 the proportions of explained variance range from 0.961 to 0.999. Note that the theoretical curves are entirely determined by that value on the size axis where the reading rate function starts, which value, in turn, is determined by visual acuity. Figure 1 shows the age comparison data of

the normal acuity groups, together with the theoretical curves. The values of explained variance are 0.925 and 0.933 and are lower than those in Figure 3, mainly because of the small variation of reading rates. It is now possible to deduce from this theoretical function the character sizes for which reading is optimal for the various groups (see Figure 4). For the normal-acuity group as a whole the highest reading rate found of 292 words per minute is reached for 2.2 mm letters; for the younger subjects it is 305 words per minute for 1.9 mm letters and for the older 248 words per minute for 2.6 mm letters. For the reduced-acuity group the highest mean reading rate found of 197 words per minute is reached for 3.7 mm letters. Finally, the poor-acuity group attains its highest mean reading rate of 144 words per minute needing 6 mm letters.

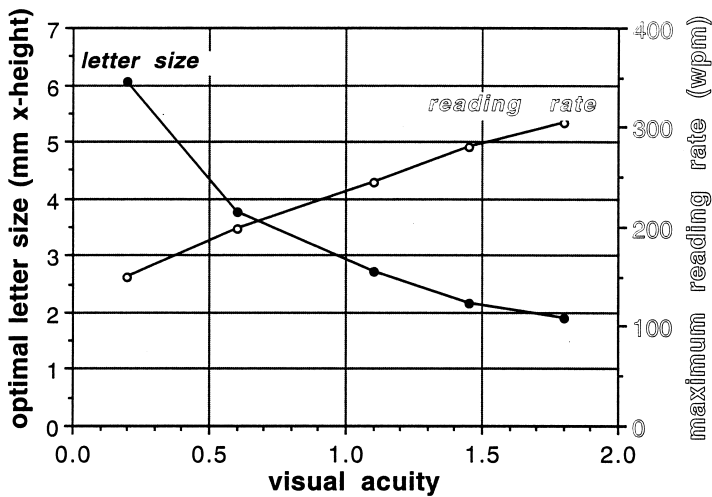


Figure 4. Optimal character size (●) and reading rate (○) attainable at optimal size as a function of visual acuity. The estimates are derived from the curves shown in figures 1 and 3.

DISCUSSION

Age and visual information processing

The results of this experiment demonstrate that (highly motivated, experienced and intelligent) people can read (simple texts) without any difficulty up to a considerable age provided their visual acuity remains on a similar level as that of younger adults. On the whole, Figure 2 shows that visual acuity is a much more important determiner of reading rate than age. The reading rates of the oldest subjects with normal acuity are still much higher than those of the youngest subjects with poor vision. As the silent reading rates of the oldest experimental group with normal acuity were relatively independent of character size, it is appropriate to attribute the decreased reading rate to a slower central processing rate rather than to optical degradation. Elliott *et al.* (1990) concluded that optical

factors such as reduced retinal illumination and increased lenticular light scatter were not primarily responsible for reduced visual sensitivity, but rather changes within the neural system. The phenomenon we are dealing with is probably one of a general decrease of functioning in old age, including visual functioning, and the fact that older adults are interested in accuracy rather than speed (Botwinick, 1978). We did not instruct our subjects to read as fast as possible (but they were told their reading rate was recorded) so they were free to choose to proceed slowly in order to maintain high accuracy levels. That they really behaved in this manner was seen in their results on a word-search-task, where old adults still were able to find all target words, but their search speed was reduced significantly (Aberson, in preparation).

The visual reading process could be affected by age as follows. The visual representation of the words might form less effectively, as a result word recognition might take more time, which, in turn, might delay the programming of saccades, which results in less accurate eye-movement. Impact on the effectiveness of the regressive line saccades caused by a reduced perceptual field would only show for the largest character sizes, if at all, and our results do not support an interaction effect of age and character size. There is no indication that integration is being affected. Salthouse (1992) did find differences in information-processing rate between young and old adults and he expected that they were connected with differences in working memory, caused by the rate at which relevant information could be activated, rather than by the ability to preserve previously activated information. So, elderly people are not expected to be handicapped in integrating the information in a sentence. Only when reading rates were extremely slow were subjects not aware of the content of the text any more. It seems likely that the cognitive effort involved in decoding the subsequent words leads to latencies that prevent memory processes achieving successful integration. Failure to understand the text could not have been the reason for subjects to stop reading, because the same number of subjects were found to stop a word-search under comparable conditions, where there was no meaningful context (Aberson, in preparation).

The instance of stopping reading is the only one in which visual acuity and age seem to interact. Old poor-acuity subjects did stop reading more often than younger ones (see Figure 5), which agrees with previous findings that old adults are harder to motivate to perform a task they perceive as senseless. In this poor-acuity group some subjects stopped after reading a sentence or two, invariably yielding reading rates of about 20 words per minute, unable to understand or recall text content. Figure 5 shows the percentage of subjects ($N = 5$) that stopped prematurely as a function of their age group.

Because in this study IQ covaried with visual acuity, we should touch lightly on IQ, reading experience and comprehension reading. A lot of deterioration of perceptual capacity will be counteracted by an increased word-knowledge and reading experience with age. Although there might be some cognitive deterioration with advancing age, at least some of the intelligence is found not to be affected by age, the so-called crystallized 'pragmatics of intelligence' (Cohen, Stanhope and Conway, 1992). Older adults have been shown to have greater deficits than younger adults when making inference that requires integrating information across sentences (Cohen, 1979). However, this was not reflected in our results on comprehension, which were independent of age. This was not different from the observation of

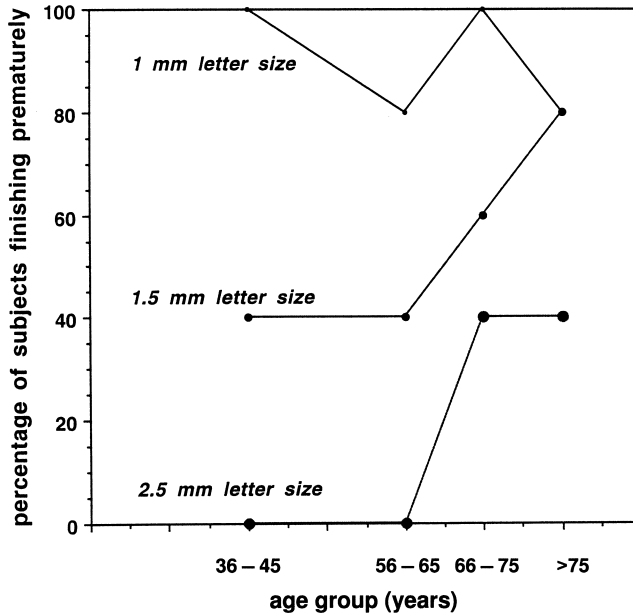


Figure 5. Percentage of poor sighted subjects who stopped reading texts with small letters after a sentence or two for the four age groups.

Harker, Hartley and Walsh (1982) that highly educated older adults did not seem to show evidence of a memory deficit when recalling information from relatively short, easy passages. In our stories only the main idea was important for understanding the text. Dixon and Bäckman (1993) reviewed research on the compensatory aspects of reading skill. Older adults scoring highly on verbal ability tests were as good as young adults in text recall and remembering the main idea, provided the text was properly structured (Meyer, Young and Bartlett, 1993). Prior knowledge is, of course, important for the amount of recall, but this was not relevant in the present situation. Differences in processing style between old (thematic/metaphoric) and young adults (verbatim meaning) could have had an influence, despite the imaginative content of the stories. Dixon *et al.* (1993) suggested three ways to maintain reading skill, i.e. continued practice, investment in compensatory mechanisms either deliberately or automatically or through substitution of alternative cognitively supporting skills. As in the present study subjects scored highly on education and reading experience and they had to read easy, entertaining stories, the differences in IQ, although significant, would be expected to have at the most only a small additional effect to the effect of visual acuity. Actually, in the linear regression the contribution of intelligence (and age) on silent reading rate was found to be minimal in comparison with visual acuity.

If our results on old age are generalized to practical situations, it should be borne in mind that as age increases the probability of visual impairment normally increases (Pitts, 1982; Greenberg and Branch, 1982). What was found for the groups with reduced and poor acuity would therefore be true for a large percentage of elderly

people. And even in this study where we artificially separated the effect of age from the effect of decreased visual acuity level, it appeared that in the normal acuity group differences in visual acuity exist which covaried with age. This could be seen as a reversed process of the development of visual acuity in young children as postulated by Brown *et al.* (1987). Visual acuity turns out to be the most important factor in determining reading rate. The effect of lower levels of visual acuity on reading rate is significant and could not be compensated for by experience or by the use of increased character sizes (see below). The remaining variation in reading rate that is observable in the various subgroups is entirely due to individual differences not to any other general variable.

Character size and visual acuity

If our model is correct, visual acuity is responsible for both the (optimal) silent reading rate and the character size for which the (optimal) reading rate is obtained. From our data we may assume that reading rates of subjects with normal acuity are relatively independent of character size, provided the characters are not too small (1 mm) and not too large (9 mm). The model enabled us to estimate proper character sizes for certain groups. The estimates could have a slight (we think negligible) positive bias due to the high illumination levels used in our experiment. Since, according to our model, reading rate is highest for smallest sufficient character sizes, a newspaper print of 1.9 mm letters will be adequate and is efficient in terms of material. However, on average this size will still not be optimal for old readers. Our model suggests a character size of 2.2 mm for the population of normal-acuity readers including the elderly, and an optimal size of 2.6 mm specifically for old readers with normal acuity. For most people with reduced acuity this might still be sufficient as long as illumination and contrast are optimal (a high non-reflecting light output and a sharp letter with high contrast). On average, however, for a reduced visual acuity a letter size of 3.7 mm x-height is probably optimal for rate of silent reading. For poor acuity subjects we know that 'newspaper character size' will no longer do. For this group of subjects our model suggests an optimal character size of 6 mm. This means that an intermediate character size is optimal for reading rate, which is in agreement with what Tinker found as long ago as 1958, and this optimum shifts to larger characters as visual acuity decreases.

Slower reading of larger character sizes might be explained by reduced parafoveal (outside an area within a visual angle of 1–2° around the fixation point) word recognition (Bouma *et al.*, 1982; Aberson and Bouma, submitted). Their results suggest an optimum for right parafoveal recognition for words with letters of between 1.7 and 4.1 mm x-height for normal acuity subjects and of between 2.7 and 6 mm x-height for subjects with reduced and poor visual acuity. Bouma (1974) explained the greater difficulty with larger characters in terms of increased lateral interference. In the current model this is understood to be caused by increased effort needed for successful visual pattern integration over a larger area. As information density is highest for small characters and lessens for larger characters, more time will be needed to integrate visually larger characters into words. This impaired parafoveal word recognition for large characters could conceivably result in reducing reading rates due to ineffective eye-movement control, leading to either more corrective eye saccades, longer saccade latencies, or more and longer fixations.

As we have seen, increasing the character size can facilitate reading. It also can enhance reading rate up to a point, but it cannot fully compensate for low visual acuity. As visual acuity becomes poorer, the character size for which optimal reading rates are obtained gets larger while at the same time optimal reading rates for those enhanced character sizes get lower. It is concluded that both decoding and integration are dependent on visual acuity and that, in the absence of specific visual defects, ageing effects in reading can be completely explained by gradual lowering of visual acuity having its origin in central mechanisms.

CONCLUSIONS

(1) Subjects over 75 years of age with adequate levels of visual acuity had a 16% (50 wpm) reduction in silent reading rate compared to younger subjects. The variance of their reading rates is significantly reduced, because of an absence of high reading rates comparable with the absence of high visual acuity levels. Differences in reading rates for the various age groups could be accurately predicted from visual acuity of those groups.

(2) Old subjects with poor visual acuity were more likely to give up reading the passages than young subjects, their reading rates being approximately 20 words per minute, at which speed they were incapable of grasping the content of what was being read.

(3) The use of very small (1 mm x-height) and very large (9 mm x-height) characters at a reading distance of 33 cm result in lower silent reading rates. Characters should in any case be larger than 1.5 mm. An optimal reading rate is reached for letters between 1.8 and 7 mm. As visual acuity deteriorates, character sizes which are optimal as regards reading rate shift to larger type sizes, from about 1.9 mm for adults with normal acuity, about 2.2 mm for all adults with normal acuity including elderly subjects, about 2.6 mm for elderly subjects with normal sight, about 3.7 mm for subjects with reduced acuity and about 6 mm for individuals with poor acuity, all at a normal reading distance of 33 cm.

(4) Increasing character size does not compensate for decreased levels of visual acuity as far as reading rates are concerned. Optimal reading rates for subjects with reduced and poor acuity did not reach those of normal-acuity subjects.

(5) Reading rate has to be at least higher than 20 words per minute, probably even twice as fast, to enable 'normal reading'. At reading rates below 20 wpm the normal reading process breaks down and does not result in any comprehension.

ACKNOWLEDGEMENTS

The research reported in this paper was in part financially supported by Grant No. 15-21-25 from ZWO, the Dutch Organisation of Pure Research, The Hague. Acknowledgements are due to Herman Bouma, who supervised the experimental

work carried out at the Institute for Perception Research, Eindhoven, Netherlands; to R. Van Hoe who advised on the use of MANOVA; and to Ch. P. Legein, the ophthalmologist who assisted in finding subjects.

REFERENCES

- ABERSON, D.H.A. and BOUMA, H. (1995) The influence of age, visual acuity and character size on word recognition. *IPO manuscript 920*, submitted for publication.
- ANSTEY, K., STANKOV, L. and LORD, S. (1993) Primary ageing, secondary ageing and intelligence. *Psychology and Ageing*, **8**, 562–570.
- BAILEY, I.L. and LOVIE, J.E. (1976) New design principles for visual acuity letter charts. *American Journal of Optometry and Physiological Optics*, **53**, 740–745.
- BLANCHARD, H.E., POLLATSEK, A. and RAYNER, K. (1989) The acquisition of parafoveal information in reading. *Perception and Psychophysics*, **46**, 85–94.
- BOTWINICK, J. (1978) *Ageing and behaviour*. New York: Springer.
- BOUMA, H. (1978) Visual search and reading: Eye movements and functional visual field: A tutorial review. *Attention and Performance VII*, Proceedings of the 7th International Symposium on Attention and Performance. J. Requin (Ed.), pp. 115–147. Hillsdale: Erlbaum.
- BOUMA, H., LEGEIN, CH.P., MÉLOTTE, H.E.M. and ZABEL, L. (1982) Is large print easy to read? *IPO Annual Progress Report*, **17**, 84–90.
- BOUMA, H. and VOGD, A.H. DE (1974) On the control of eye saccades in reading. *Vision Research*, **14**, 273–284.
- BOUWHUIS, D.G. and BOUMA, H. (1979) Visual recognition of three-letter words as derived from the recognition of the constituent letters. *Perception and Psychophysics*, **25**, 12–22.
- BROWN, M., DOBSON, V. and MAIER, J. (1987) Visual acuity of human infants at scotopic, mesopic and photopic luminances. *Vision Research*, **27**, 1845–1858.
- COHEN, G. (1979) Language comprehension in old age. *Cognitive Psychology*, **11**, 412–429.
- COHEN, G. and FAULKNER, D. (1983) Word recognition: age differences in contextual facilitation effects. *British Journal of Psychology*, **74**, 231–251.
- COHEN, G., STANHOPE, N. and CONWAY, M.A. (1992) Age differences in retention of knowledge by young and elderly students. *British Journal of Developmental Psychology*, **10**, 153–164.
- CORSO, J.F. (1971) Sensory processes and age effects in normal adults. *Journal of Gerontology*, **26**, 90–105.
- CRAIK, F.I.M. and BOSMAN, E.A. (1992) Age-related changes in memory and learning. In H. Bouma and J.A.M. Graafmans (Eds.) *Gerontechnology*. Amsterdam: IOS Press.
- DIXON, R.A. and BÄCKMAN, L. (1993) Reading and memory for prose in adulthood: issues of expertise and compensation. In Yussen, S.R. and Smith, M.C. (eds.) *Reading across the life span*. New York: Springer Verlag.
- ELLIOTT, D., WHITAKER, D. and MACVEIGH, D. (1990) Neural contribution to spatiotemporal contrast sensitivity decline in healthy ageing eyes. *Vision Research*, **30**, 541–547.
- FLESCHE, R.F. (1951) *How to test readability*. New York: Harper.
- FOZARD, J.L., WOLF, E., BELL, B., MCFARLAND, R.A. and PODOLSKY, S. (1977) Visual perception and communication. In: J.E. Birren and K. Warner Schaie (Eds.) *Handbook on the psychology of ageing*. New York: Van Nostrand Reinhold Company.
- GITTINGS, N.S. and FOZARD, J.L. (1986) Age related changes in visual acuity. *Experimental Gerontology*, **21**, 423–433.
- GREENBERG, D.A. and BRANCH, C.G. (1982) A review of methodological issues concerning incidence and prevalence data of visual deterioration in elders. In: R. Sekuler, D. Kline and K. Dismukes (Eds.), *Modern aging research*, New York: Alan R. Liss Inc.
- HARKER, J.O., HARTLEY, J.T. and WALSH, D.A. (1982) Understanding discourse: a life-span approach. *Advances in Reading/Language Research*, **1**, 155–202.
- INHOFF, A.W. (1989) Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, **15**, 544–555.
- JUST, M.A. and CARPENTER, P.A. (1980) A theory of reading: from eye fixations to comprehension. *Psychological Review*, **87**, 329–354.

- LEGEIN, CH.P. and BOUMA, H. (1982) Reading and the ophthalmologist. An introduction into the complex phenomenon of ordinary reading as a guideline for analysis and treatment of disabled readers. *Documenta Ophthalmologica*, **53**, 123–157.
- LEGGE, G.E., PELLI, D.G., RUBIN, G.S. and SCHLESKE, M.M. (1985a) Psychophysics of reading I. Normal vision. *Vision Research*, **25**, 239–252.
- LEGGE, G.E., RUBIN, G.S., PELLI, D.G. and SCHLESKE, M.M. (1985b) Psychophysics of reading. II. Low vision. *Vision Research*, **25**, 253–266.
- LEGGE, G.E. and RUBIN, G.S. (1986) Psychophysics of reading. IV. Wavelength effects in normal and low vision. *Journal of the Optical Society of America*, **A3**, 40–51.
- LIMA, S.D. and INHOFF, A.W. (1985) Lexical access during eye fixations in reading: effects of word-initial letter sequence. *Journal of Experimental Psychology: Human Perception and Performance*, **11**, 272–285.
- McCONKIE, G.W. and RAYNER, K. (1975) The span of effective stimulus during a fixation in reading. *Perception and Psychophysics*, **17**, 578–586.
- McCONKIE, G.W. and RAYNER, K. (1976) Identifying the span of the effective stimulus in reading: Literature review and theories of reading. In: H. Singer and R.B. Ruddell (Eds.) *Theoretical models and processes of reading*. Newark, Del: International Reading Association.
- MEYER, B.J.F., YOUNG, C.J. and BARTLETT, B.J. (1993) Reading comprehension and the use of text structure across the adult life span. In: *Reading across the life span*. Yussen, S.R. and Smith, M.C. (eds.).
- MORRIS, R.K., RAYNER, K. and POLLATSEK, A. (1990) Eye movement guidance in reading: the role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance*, **16**, 268–281.
- MYERSON, J., HALE, S., WAGSTAF, D., POON, L.W. and SMITH, G.A. (1990) The information-loss model: a mathematical theory of age-related cognitive slowing. *Psychological Review*, **97**, 475–487.
- O'BRIEN, R.G. and KISTER KAISER, M. (1975) MANOVA method for analyzing repeated measures designs: an extensive primer. *Psychological Bulletin*, **97**, 316–333.
- OWSLEY, C., SEKULER, R. and SIEMSEN, D. (1983) Contrast sensitivity throughout adulthood. *Vision Research*, **23**, 689–699.
- PELLI, E. (1992) Limitations of image enhancement for the visually impaired. *Optometry and Vision Science*, **69**, 15–24.
- PELLI, D.G., LEGGE, G.E. and SCHLESKE, M.M. (1985) Psychophysics of Reading. III. A fibrescope low-vision reading aid. *Investigative Ophthalmology and Visual Science*, **26**, 451–463.
- PITTS, D.G. (1982) The effects of ageing on selected visual functions: dark adaptations, visual acuity, stereopsis and brightness contrast. In: R. Sekuler, D. Kline and K. Dismukes (Eds.): *Ageing and human visual function: Modern ageing research*, **2**, New York: Alan R. Liss, Inc.
- PULLING, N.H., WOLF, E., STURGIS, S.P., VAILLANCOURT, D.R. and DOLLIVER, J.J. (1980) Headlight glare resistance and driver age. *Human Factors*, **22**, 103–112.
- RAYNER, K. (1978) Eye movements in reading and information processing. *Psychological Bulletin*, **85**, 618–660.
- RAYNER, K., McCONKIE, G.W. and ZOLA, D. (1980) Integrating information across eye movements. *Cognitive Psychology*, **12**, 206–228.
- RAYNER, K., WELL, A.D., POLLATSEK, A. and BERTERA, J.H. (1982) The availability of useful information to the right of the fixation in reading. *Perception and Psychophysics*, **31**, 537–550.
- RUNSTRÖM, M.M. and EPERJESI, F. (1995) Is there a need for binocular vision evaluation in low vision? *Ophthalmic and Physiological Optics*, **15**, 525–528.
- SALTHOUSE, T.A. (1992) Influence of processing rate on adult age differences in working memory. *Acta Psychologica*, **79**, 155–170.
- SALTHOUSE, T.A. and SOMBERG, B.L. (1982) Skilled performance: effects of adult age and experience on elementary processes. *Journal of Experimental Psychology: General*, **111**, 176–207.
- SANDERS, A.F. (1963) *The selective process in the functional visual field*. Soesterberg: Institute for Perception RVO-TNO, National Defence Research Organization.
- SHARPE, J.A. and SILVESTER, T.O. (1978) Effect of ageing on horizontal smooth pursuit. *Investigative Ophthalmology*, **17**, 465–8.
- SHARPE, J.A. and ZACKON, D.H. (1987) Senescent saccades. Effects of ageing on their accuracy and velocity. *Acta Otolaryngologica*, **104**, 422–428.
- SLOANE, A.E. and KRAUT, J.A. (1975) The pleasures of reading need not diminish with age. *Geriatrics*, **30**, 117–118.

- SLOANE, M.E., OWSLEY, C. and ALVAREZ, S.L. (1988) Aging, senile miosis and spatial contrast sensitivity at low luminance. *Vision Research*, **28**, 1235–1246.
- SNIJDERS, J.TH. and VERHAGE, F. (1962) *Groninger Intelligentie Test*. Lisse: Swets & Zeitlinger.
- SPEAR, P.D. (1993) Neural bases of visual deficits during aging. *Vision Research*, **33**, 2589–2609.
- TINKER, M.A. (1958) Recent studies of eye movements in reading. *Psychological Bulletin*, **55**, 215–231.
- TINKER, M.A. (1963) *Legibility of Print*. Ames, Iowa: Iowa University Press.
- VANDERPLAS, J.M. and VANDERPLAS, J.H. (1980) Some factors affecting legibility of printed materials for older adults. *Perceptual and Motor Skills*, **50**, 923–932.
- WARABI, T., KASE, M. and KATO, T. (1984) Effect of aging on the accuracy of visually guided saccadic eye movement. *Annals of Neurology*, **16**, 449–54.
- WEALE, R.A. (1963) *The ageing eye*. London: H.K.Lewis.
- WEALE, R.A. (1986) Ageing and vision. *Vision Research*, **26**, 1507–1512.
- WILKINS, A.J. and NIMMO-SMITH, M.I. (1987) The clarity and comfort of printed text. *Ergonomics*, **30**, 1705–1720.

Address for correspondence: DR. DIEUWKE H.A. ABERSON, Oudegracht 371, 3511 PG Utrecht, Netherlands. Email: aberson@let.ruu.nl