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Simulation of artificial vision: I. Eccentric reading of isolated words, and perceptual learning

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Abstract

Simulations of artificial vision were performed to assess "minimum requirements for useful artificial vision". Retinal prostheses will be implanted at a fixed (and probably eccentric) location of the retina. To mimic this condition on normal observers, we projected stimuli of various sizes and content on a defined stabilised area of the visual field. In experiment 1, we asked subjects to read isolated 4-letter words presented at various degrees of pixelisation and at various eccentricities. Reading performance dropped abruptly when the number of pixels was reduced below a certain threshold. For central reading, a viewing area containing about 300 pixels was necessary for close to perfect reading (>90% correctly read words). At eccentricities beyond 10°, close to perfect reading was never achieved even if more than 300 pixels were used. A control experiment using isolated letter recognition in the same conditions suggested that lower reading performance at high eccentricity was in part due to the "crowding effect". In experiment 2, we investigated whether the task of eccentric reading under such specific conditions could be improved by training. Two subjects, naive to this task, were trained to read pixelised 4-letter words presented at 15° eccentricity. Reading performance of both subjects increased impressively throughout the experiment. Low initial reading scores (range 6%–23% correct) improved impressively (range 64%–85% correct) after about one month of training (about 1 h/day). Control tests demonstrated that the learning process consisted essentially in an adaptation to use an eccentric area of the retina for reading. These results indicate that functional retinal implants consisting of more than 300 stimulation contacts will be needed. They might successfully restore some reading abilities in blind patients, even if they have to be placed outside the foveal area. Reaching optimal performance may, however, require a significant adaptation process.

Keywords: Visual *prosthesis*; Simulation; Reading performance; Eccentric reading; Learning

1. Introduction

Over the last few years, several research groups have initiated important projects aiming at the development of visual prostheses for the blind (Chow & Chow, 1997; Dobelle, 2000; Humayun & de Juan, 1998; Normann, Maynard, Rousche, & Warren, 1999; Rizzo & Wyatt, 1997; Veraart et al., 1998; Zrenner et al., 1999). Increasing interest in this domain is essentially due to recent progress in micro-technology. One issue of major importance, when considering the conception of a visual prosthesis, is the determination of *minimum requirements for useful artificial vision*. We used simulations of artificial vision with normal subjects to assess this issue. Our simulations were designed to mimic artificial vision produced by a retinal prosthesis, but some of the results may also be of interest for prostheses located at other levels of the visual pathways (e.g. stimulating the optic nerve or the visual cortex).

In everyday life, current visual tasks can be divided into three main classes: recognition of (small) shapes as it is specifically required for reading, localisation of objects in 3D familiar-scale environments and spatial orientation including whole body mobility. All of them have to be thoroughly studied to determine what is the minimal visual information required to restore a useful visual function. In this study, we focussed on reading.

Understanding the fundamentals of reading has received a lot of attention. One of the main research

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centres in this field is the laboratory for low vision research at the University of Minnesota. These authors have systematically studied various aspects of reading psychophysics in normal subjects and low vision patients. For normal subjects, Legge, Pelli, Rubin, and Schleske (1985) reported that maximum reading rates are achieved for characters subtending 0.3°–2° of visual angle; that reading rate increases with field size, but only up to 4 characters, independently of character size; that reading rates increase with sample density, but only up to a critical density which depends on character size, when the text is matrix sampled or pixelised. Reading was also found to be very tolerant to either luminance or colour contrast reductions (Legge & Rubin, 1986; Legge, Rubin, & Luebker, 1987; Legge, Parish, Luebker, & Wurm, 1990). At very low (<10%) luminance contrast however, reading speed drops due to prolonged fixation times and to an increased number of saccades, presumably related to a reduced visual span (Legge, Ahn, Klitz, & Luebker, 1997). When testing the effect of print size on reading speed in normal peripheral vision, it was found that the use of larger characters improves peripheral reading to some extent, up to a critical print size (Chung, Mansfield, & Legge, 1998). But maximum reading speed also decreased from about 808 words/min for foveal vision to about 135 words/min for peripheral vision at 20° eccentricity. [1] Thus print size was not found to be the only factor limiting maximum reading speed in normal peripheral vision, contradicting the scaling hypothesis (Latham & Whitaker, 1996; Toet & Levi, 1992) which implies that peripheral word recognition can be made equal to that at the fovea by increasing print size.

In low-vision patients, reading is similar to normal reading in several aspects (Legge, Rubin, Pelli, & Schleske, 1985; Legge et al., 1990; Legge et al., 1997; Rubin & Legge, 1989), but difficult to predict on the basis of routine clinical evaluations (Legge, Ross, Isenberg, & La May, 1992). As a rule however, it can be stated that low-vision patients with central field defects achieve lower reading rates than those with preserved central fields (Legge et al., 1985; Rubin & Legge, 1989).

The studies quoted above (as well as many others) have led to the identification of a series of important parameters that are critical for reading in normal and low vision subjects. To our knowledge, there is however only a limited number of studies, which were specifically oriented towards the development of visual prostheses. Cha, Horch, Normann, and Boman (1992) used a pixelised vision system to simulate artificial vision in normal subjects. Their results showed that a 25×25 array of pixels representing 4-letters of text projected on a foveal visual field of 1.7° is sufficient to provide reading rates near 170 words/min using scrolled text, and near 100 words/min using fixed text. This investigation was conducted within the frame of a project, which aimed at developing a cortical visual implant (Normann et al., 1999). Another research group, developing a retinal implant to stimulate remaining retinal neurons in photoreceptor degenerative diseases (Humayun et al., 1999), conducted experiments on the properties of pixelised vision at the Johns Hopkins University of Baltimore (Dagnielie, Thompson, Barnett, & Zhang, 2000; Thompson, Barnett, Humayun, & Dagnelie, 2000). Reading speed and facial recognition were measured by simulating prosthetic vision in the central visual field using a head mounted video display. Subjects used eye movements to scan the stimuli through a pixelising grid. Several grid parameters were explored. Results demonstrated reading speeds up to 100 words/min, which dropped off (a) when the grid size covered less than 4 letters, (b) when a grid density of less than 4 pixels per letter width was used, or (c) when more than 50% of the pixels were randomly turned off.

In all previous experiments attempting to mimic conditions of artificial vision, eye movements could be used to scan a target with the fovea. However, the anatomo-physiology of the retina does not favour a foveal location for such prostheses (see e.g. Sjöstrand, Olsson, Popovic, & Conradi, 1999). Retinal implants are primarily designed to stimulate neurones of the inner retinal layers in cases of photoreceptor loss (e.g. retinitis pigmentosa). Surviving bipolar and/or ganglion cells are the targets for electrical stimulation. In the central fovea, these neurons are not present. In the parafovea, they are arranged in several superimposed layers that makes it difficult to activate them in predictable patterns. The best sites for retinotopic activation without major distortion are located beyond the parafoveal region. Such eccentric locations as well as the fact that a retinal implant will stimulate a fixed area of the retina have apparently not yet been fully taken into consideration. The aim of the present research work was to assess reading performance with a system projecting stimuli onto defined, stabilised areas of the visual field placed at various eccentricities. In experiment 1, we studied the influence of stimulus pixelisation, stimulus eccentricity and stimulus size on reading performance. In experiment 2, we investigated whether the task of eccentric reading under such specific conditions could be improved by training.

2. General methods

2.1. Subjects

All subjects were normal volunteers, recruited from the staff of the Geneva University Eye Clinic. Age ran-

[1] Such high reading rates were achieved by using rapid serial visual presentation (RSVP).

Fig. 1. The SMI EyeLink system. Three cameras are attached to a headband. Two cameras are recording eye movements. One camera is recording IR light points from each corner of the screen to monitor head position relative to the screen. On this basis, the EyeLink software calculates online the gaze position in screen coordinates. In this example, a 4-letter word is projected on a stabilised retinal area located at 5° eccentricity in the lower visual field. The horizontal line crossing the screen represents a fixation aid for the subject (used in experiment 1).

ged from 25 to 47 years. All had normal or corrected to normal visual acuity of 20/20 in the tested eye. All of them were native French speakers or had perfect knowledge of French.

All experiments were conducted according to the ethical recommendations of the Declaration of Helsinki and were approved by local ethical authorities.

2.2. Experimental set-up

To simulate visual percepts produced by a retinal implant, images were projected on a defined and stabilised area of the retina. Target image stabilisation in the visual field was achieved by online compensation of the gaze position on a fast computer display using a high speed video based eye and head-tracking system, the SMI EyeLink Gaze tracking system (SensoMotoric Instruments GmbH, Teltow/Berlin, Germany; see Fig. 1).

The experimental set-up consisted of two computers and a headband mounted measuring unit. The "subject's PC" (PIII-450 equipped with a Matrox G200 graphics card) was used to generate the stimuli on a 22" ELSA Ecomo 22H99 screen set to a resolution of 600×800 pixels at a refresh rate of 160 Hz. It was connected via Ethernet to the "operator's PC", a Compaq Deskpro EP (Celeron-400), which contained the hardware and software to collect and compute the data from the three head mounted cameras. Gaze position data in screen coordinates were transmitted to the subject PC every 4 ms (250 Hz), and were available for further computing with a time delay of less than 10 ms.

The system worked in the following way: gaze position was used to move the target stimuli (bitmap images) on the stimulation screen according to the eye movements of the subject. Images could thus be steadily projected onto a defined (central or eccentric) area of the retina. A pilot study (Bagnoud, Sommerhalder, Pelizzone, & Safran, 2001) demonstrated that this experimental set-up allowed to accurately stabilise targets in the visual field by online compensation of the gaze position.

2.3. Generation and presentation of the stimuli

Stimuli were presented in rectangular white areas (viewing areas), which were filled with black 4-letter words of common French language (including accented characters and capital letters for proper names). We used 4-letter words for our experiments because this was considered to be the minimum letter-sequence allowing close to normal reading speeds (Legge et al., 1985). [2] We used the largest possible font size fitting within the viewing area. We chose the proportionally spaced

[2] Although maximum reading speeds would be favored by viewing areas containing a higher number of characters, as quoted by several authors, the presentation of only 4 letters allowed to use a large character size favoring peripheral reading.

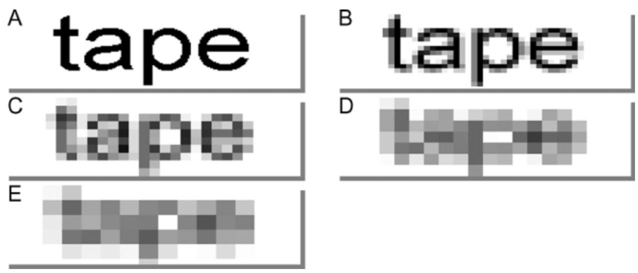

Fig. 2. Presentation of the 4-letter word "tape" illustrating the five degrees of pixelisation used in experiment 1: (A) maximum screen resolution, (B) 875 pixels, (C) 286 pixels, (D) 140 pixels, (E) 83 pixels. The pixel numbers indicate the total number of pixels in the viewing area.

Helvetica (i.e. Arial) font style because it is commonly used for text printing, and has been shown to provide good reading conditions to low vision subjects (Buultjens, Aitken, Ravenscroft, & Carey, 1999).

The stimuli used for the experiments were pre-processed bitmap images, which had been pixelised [3] (mosaic pixelisation) to simulate the reduced information content due to a limited number of parallel processing channels in retinal prostheses. Fig. 2 shows an example of one of our stimuli at different pixelisations. Images were generated using Adobe Photoshop® 5.5 software.

The subjects were comfortably seated facing the screen at an eye-to-screen distance of 57 cm. At this distance, the 30 cm × 40 cm surface of the screen subtends a visual angle of 30° × 40°, 1° corresponding to 20 screen pixels at the screen resolution of 600 × 800. The camera monitoring the eye was positioned so that the pupil was clearly visible and well defined at any gaze position. At the beginning of each run the eye to screen distance was checked, adjusted if needed, and a standard 9-point calibration of the eye-tracker was performed. Then, a block of 50 words, randomly chosen among a library of 500 common French 4-letter words was presented. Subjects were requested not to move during the run.

Reference point for the stimulus eccentricity was the centre of the viewing area. Eccentric stimuli were presented in the lower visual field (Fig. 3). This offered at least two practical advantages: (1) the retinal eccentricity of each letter varies less when a word is projected below or above the fixation point than when projected to the left or the right; and (2) the lower visual field is most commonly used for eccentric reading (see e.g. Chung et al., 1998). For each item of the run, the subject had to say the word he/she recognised. The response (right or wrong) was entered by the examiner into the operator PC and stored for further analysis. After each single word presentation, the calibration was checked for possible drifts or artefactual movements, and slightly corrected if needed, to insure an exact control of the target image position during the entire experiment.

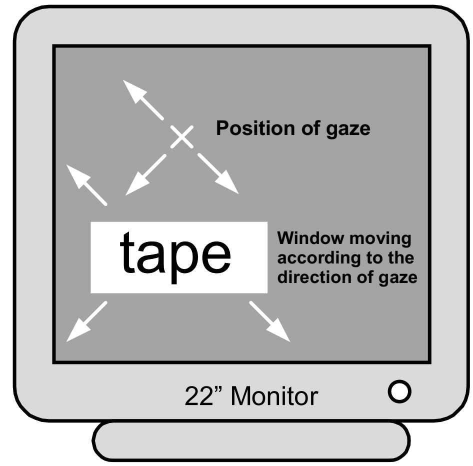

Fig. 3. The stimulation screen seen by the subject. The viewing area, a white surface with black text, was moving on the screen according to the direction of gaze and with a constant offset (eccentricity). The background of the remaining screen area was in a grey colour corresponding to the mean grey level of the target windows. The viewing area subtended in this case a visual field of 20° × 7°.

2.4. Data analysis

Reading performance was determined as the percentage score of fully recognised words out of each 50-item block. Results expressed on such a proportional percentage scale are, however, not suitable for statistical analysis. It is well known that with proportional scales, variance is not correlated with the mean. In other words, the data are not normally distributed around the mean and scale values are not linear in relation to the test variability. One can solve this problem by using an arcsine transformation. Studebaker (1985) proposed to use so-called "rationalised arcsine units" (rau), producing values that are numerically close to the original percentage range, while retaining all of the desirable properties of the arcsine transform. For example, for a sample size of 50 responses, 0% correct corresponds to −16.5 rau, 50% to correct to 50 rau and 100% correct to 116.5 rau. All data were statistically analysed using scores expressed in rau. On the right ordinates of the graphs, however, and also for the description of the results, values on the original percent-correct scale are indicated for better clarity.

3. Experiment 1

3.1. Specific methods

In experiment 1, reading performance was assessed as a function of a series of variables, each being potentially

[3] Mosaic pixelisation (i.e. square pixels of uniform grey level) was used. Such simple patterns were adequate to simulate the reduced information content (e.g. finite quantisation) of the stimuli, but were not intended to mimic the nature (e.g. profile, shape, colour, etc.) of the perceptual pixels elicited by electrical activation of the retina.

an important parameter of prosthetic vision. First, the number of contacts in the prosthesis: five different degrees of pixelisation were tested, viewing areas of maximum screen resolution, 875, 286, 140 and 83 pixels (see also Fig. 2). [4] Second, retinal placement of the prosthesis: five different eccentricities in the lower visual field were tested, 0°, 5°, 10°, 15° and 20°. Third, size of the prosthesis: two viewing areas were investigated. The large area, subtending a visual field of 20° × 7°, allowed the use of a print size greater than the critical print size needed for optimal reading performance at 20° eccentricity (Chung et al., 1998). The height of a small letter 'x' used on this large viewing area corresponded to a visual angle of 3.6°. The small area, subtending 10° × 3.5°, corresponded to a surface of approximately 3 mm × 1 mm on the retina, and was used to represent the surface of a smaller, possibly more realistic retinal prosthesis that would be manageable surgically. The height of a small letter 'x' used on this small viewing area corresponded to a visual angle of 1.8°. Note that using the same number of pixels on both viewing areas implied that pixels were larger (4 times) on the large viewing area.

All tests were conducted monocularly on five normal volunteers. Each subject performed one run (consisting of a 50-word block) in each condition. Testing always started at the lowest eccentricity, using maximum screen resolution first, then successively coarser resolutions. Then, the same procedure was repeated using the next eccentricity. Possible global learning effects would therefore favour greater performance at low pixel numbers and high eccentricities. Each word was presented during 3 s. When eccentric stimulus presentation was used, a fixation aid (consisting of a horizontal red filament crossing the screen) was installed to make it easier for the inexperienced subject to keep the target on screen.

3.2. Reading performance on the larger viewing area (20° × 7°)

Mean reading performance versus pixel number for various eccentricities on the larger viewing area is presented in Fig. 4a. In central vision, reading performance of 4-letter words was almost perfect (i.e. higher than 90% correct) for pixelisations down to 286 pixels. At lower resolution, reading performance dropped abruptly. This result indicates that approximately 300 pixels are necessary to transmit the relevant information under optimal conditions. In peripheral vision, maximum reading performance decreased with increasing eccentricity. At an eccentricity of 10°, almost perfect reading (better than 90% correct) was still possible at high pixel resolutions. At eccentricities of 15° and 20°, almost perfect reading was never achieved even at high resolutions. Maximum reading performance was limited to values of 88% and 63% correctly read words, respectively.

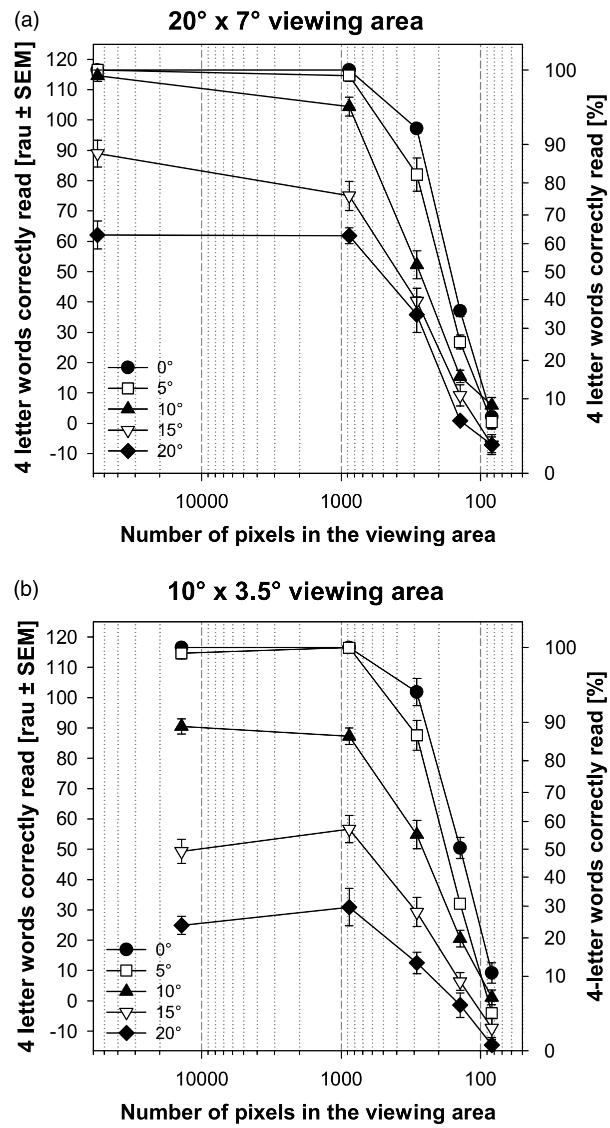

Fig. 4. Performance for single 4-letter word reading versus number of pixels in a stabilised viewing area of (a) 20° × 7° and (b) 10° × 3.5°. Mean reading scores in rationalised arcsine units ± SEM (left scale) and in percent (right scale) for five normal subjects at five eccentricities in the lower visual field. At maximum screen resolution, the large viewing area contained 4 times more pixels than the small viewing area. Otherwise, tests were performed at equal pixel resolution for both viewing areas.

3.3. Reading performance on the smaller viewing area (10° × 3.5°)

Mean reading performance versus pixel number for various eccentricities on the smaller viewing area is

[4] Mosaic pixelisation in Adobe Photoshop® reduces screen resolution by an integer factor. Therefore in our experimental conditions 875 pixels can be viewed as an array of 50 × 17.5 pixels, 286 pixels as 28.6 × 10 pixels, 140 as 20 × 7 pixels and 83 pixels as 15.4 × 5.4 pixels.

presented in Fig. 4b. In central vision, results with the smaller viewing area were very similar to those with the larger area. Reading performance of 4-letter words was almost perfect (or higher than 90% correct) for pixelisations down to 286 pixels. Then, it dropped abruptly. The same limiting criterion of about 300 pixels was found to transmit the relevant information. In peripheral vision, the decrease in maximum reading performance with increasing eccentricity was more pronounced than on the larger viewing area: at eccentricities of 10°, 15° and 20°, maximum reading performance was limited to values of 89%, 57% and 30% correct, respectively.

3.4. Normalised data on both viewing areas

The raw observations presented in Fig. 4 demonstrate that both number of pixels and eccentricity of the stimuli affected reading performance of 4-letter words in our experiments. In order to compare the effect of the pixel number at different eccentricities, we normalised the data to the values obtained at maximum screen resolution (Fig. 5). These normalised data demonstrate that the pixel number affected reading performance very similarly at all eccentricities and on both viewing areas. This result is consistent with the fact that the number of pixels influences directly the information content of the source image. The eccentricity of the stimulus, however, seems to affect the way information is processed by the visual system, and appears to limit maximum reading performance.

3.5. Single letter recognition versus 4-letter word reading

At eccentricities of 10° and more, most subjects spontaneously reported that they had problems recognising letters occurring in the middle of the words. This suggested that letters closely flanked by others were more difficult to identify. To check this point, we designed an additional experiment, using isolated letter stimuli instead of 4-letter words. In brief, isolated single letters of identical font type and size as for the word experiments were presented on the small viewing area. The overall surface of the viewing area did not change and it contained the same total number of pixels as for the word experiments. Blocks of 50 letters, chosen among the French alphabet and according to their frequency of use in our pool of 500 words, were randomly presented to five new subjects. The results of this additional experiment are presented in Fig. 6. Up to an eccentricity of 15°, isolated letter recognition was almost independent of eccentricity. At 20° eccentricity, maximum letter recognition was still about 90% correct for high pixel resolutions. Fig. 7 compares reading performance of isolated letters to that of 4-letter words

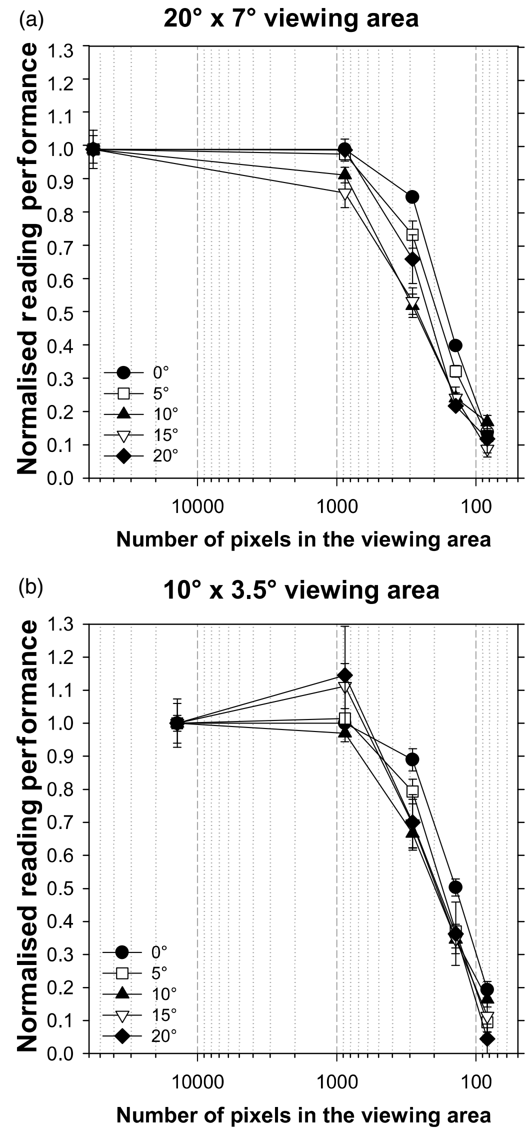

Fig. 5. Normalised reading performance for single 4-letter words versus number of pixels in a stabilised viewing area of (a) 20° × 7° and (b) 10° × 3.5°. Mean relative reading scores ± SEM for five normal subjects at five eccentricities in the lower visual field. The data are normalised to the mean reading performance values at maximum screen resolution.

at 286 pixel resolution on the small viewing area. It appeared that isolated letter recognition was much less affected by eccentricity than word reading. In an attempt to compare both results, we computed, as a first approximation, the intrinsic probability to correctly identify 4 isolated letters in a successive sequence. This rough estimation still falls short to account for the very low scores observed in the word-reading task. The two tasks are difficult to compare quantitatively in an accurate manner, but this observation suggests that 4-letter word reading was significantly reduced at high eccentricities by the fact that the letters to be recognised

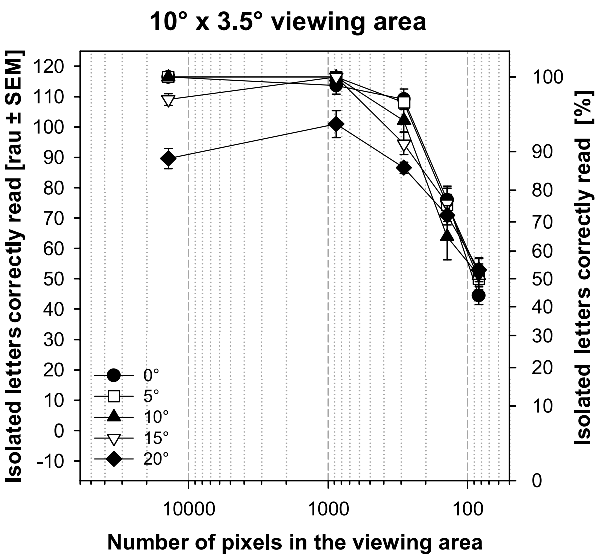

Fig. 6. Performance in isolated letter recognition versus number of pixels in the stabilised viewing area of 10° × 3.5° at five eccentricities in the lower visual field. Mean letter recognition scores in rau ± SEM (left scale) and in percent (right scale) for five normal subjects.

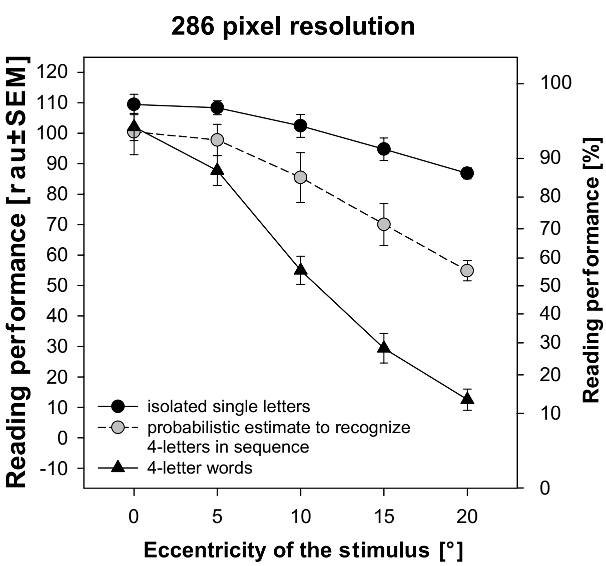

Fig. 7. Reading performance versus eccentricity for stimuli presented on the smaller viewing area (10° × 3.5°) containing 286 pixels. Results of isolated letter recognition are compared to results of 4-letter word reading. Mean performance in rau ± SEM (left scale) and in percent (right scale) for five normal subjects. The dotted line indicates the probabilistic prediction to recognise 4-letters in sequence on the basis of the probability to recognise single isolated letters ($p_{\text{words}} = p^4_{\text{letters}}$). Note that this simple estimate indicates a lower limit (e.g. some words may be identified without requiring recognition of all 4-letters).

are flanked by others. The "crowding effect" [5] (Tychsen, 1992) may be the underlying fundamental mechanism.

[5] Increased difficulty in recognising words made up of closely spaced letters, when presented in the peripheral visual field.

Finally, it should also be noted, that at high eccentricities, isolated letter recognition was significantly better at a target resolution of 875 pixels than at maximum screen resolution (Fig. 6; $p = 0.016$ at 15° eccentricity, $p = 0.018$ at 20° eccentricity). The data for 4-letter word reading on the small viewing area (Fig. 4b) show the same trend. This finding may indicate, that at high eccentricities a certain blur of the target (due to pixelisation) leads to better performance, if the letter size is below the critical print size. A recent study by Li, Nugent, and Peli (2001) compared letter recognition of jagged (pixelised) and smoothed (anti-aliased) letters on a CRT display. They found no significant difference between the two conditions in peripheral vision up to 12.5° eccentricity. While the stimuli used by Li and co-workers are not exactly comparable with the stimuli we used, the present result suggests that observable differences may appear only at higher eccentricities (15° and more).

4. Experiment 2

Results collected in experiment 1 might underestimate possible performances, especially at high eccentricities, because normal subjects were not used to eccentric reading. Blind patients, potential recipients of retinal implants, will have time to fully adapt to the use of their prosthesis. We therefore investigated in experiment 2 the effect of training on eccentric reading.

4.1. Specific methods

We attempted to choose a test condition mimicking as closely as possible a realistic retinal prosthesis. According to Sjöstrand et al. (1999) a radial one-to-one connection between photoreceptors, bipolar cells and ganglion cells is not guaranteed for eccentricities smaller than about 10°. Retinotopic activation without major distortion is essential if one wants to avoid complex preprocessing of the light falling on the retina. We therefore decided to investigate the effects of training on a viewing area placed at 15° eccentricity in the lower visual field (corresponding to a surgically as well as physiologically favourable location on the retina). We chose the smaller viewing area of 10° × 3.5° (corresponding to a surgically manageable surface of 3 × 1 mm^2 on the retina) containing 286 pixels (corresponding to a number of pixels allowing close to perfect word recognition in central vision and representing a number of contacts which is manageable with present technology). Under such conditions in experiment 1, subjects could correctly identify between 20% and 48% of the words. This level of performance was clearly above chance level, but insufficient to provide useful function. For comparison, two additional experimental conditions on the same viewing area were used: (a) stimuli containing the same number of pixels (286 pixels), but presented at an eccentricity of 0° (central reading); (b) stimuli presented at the same eccentricity (15°), but containing 14,000 pixels (maximum screen resolution).

Two young female subjects, both 27 years old, participated in this experiment. [6] Subject EO performed all tests in binocular condition, whereas Subject AR performed all tests in monocular condition. [7] They had not participated in any of the previous studies on eccentric reading.

Three experimental sessions were conducted each working day of the week (5 days a week). Each session included one run (consisting of a 50-word block) in each of the following three successive conditions: first, 286 pixels at 0° eccentricity; second, 14,000 pixels at 15° eccentricity; and third, 286 pixels at 15° eccentricity. Thus, the easiest condition was tested first, and the most difficult last, so that possible within-session learning effects would favour results in the most difficult condition. Each experimental session lasted about 20 min, the three sessions representing about 1 h of daily training. A total of 69 sessions were conducted with each subject. Except for weekends, the regular daily flow of sessions was interrupted once (AR), or twice (EO), for 3-day vacations.

The presentation time of each stimulus was limited to 10 s, but subjects were instructed to press a key as soon as they had recognised the projected word. The response time was recorded together with the nature of the subject's response ('right' or 'wrong'). At the end of each run, reading performance (expressed in number of correctly recognised words) and mean response time (expressed in seconds, on the basis of all 50 trials) were automatically computed.

Learning curves were established for each experimental condition on the basis of reading scores and also on the basis of mean response time. Data were fitted using the non-linear regression function

$$y = y_0 + a(1 - e^{-bx}).$$

To determine if time (expressed as session number) had a statistically significant effect on performance we used a simple linear correlation (Pearson's correlation).

[6] Since the main goal of the experiment was to show in a general way, that performance in eccentric reading can be improved by training, 2 subjects were estimated to be sufficient to demonstrate such an effect.

[7] Retinal implants will certainly essentially be used monocularly. It was, however, interesting to compare monocular to binocular learning in normal subjects who generally use binocular vision.

4.2. *Learning effects on eccentric reading of pixelised words*

Fig. 8 presents reading performance versus session number in the main condition (286-pixel resolution at 15° eccentricity). We observed impressive learning effects on both subjects. Both began the experiment with low reading scores and improved over time by about 60% points. These improvements were highly statistically significant (Pearson's correlation: $r = 0.80$, $p < 0.0001$ for EO and $r = 0.86$, $p < 0.0001$ for AR).

Experimental data were fitted with the exponential function presented in the methods section to average session-to-session variability. The fits revealed some noticeable individual differences. At the very beginning of the learning period, subject EO was able to identify

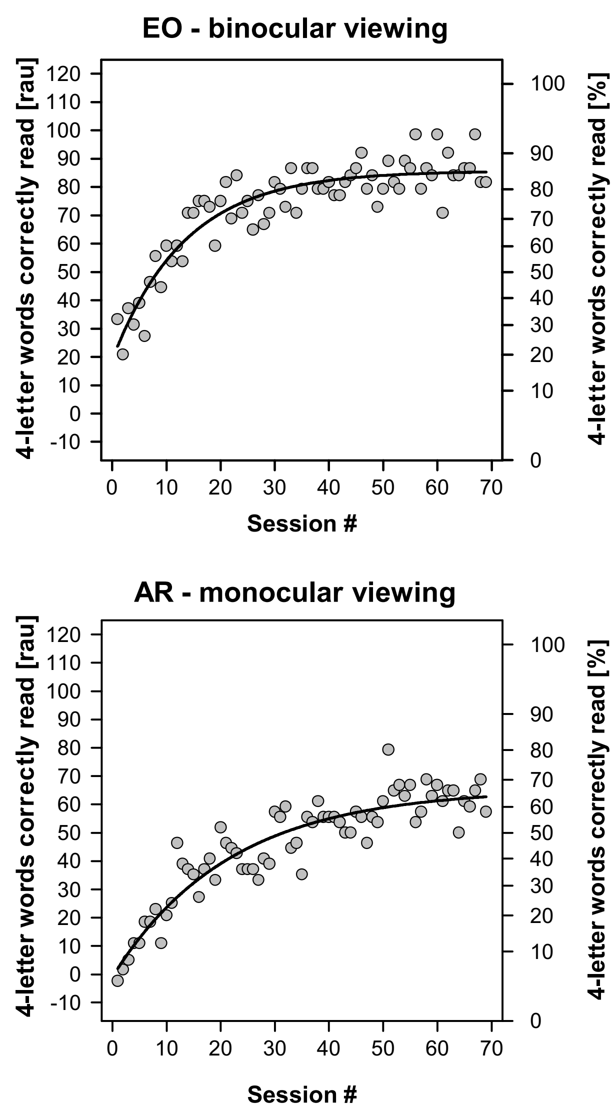

Fig. 8. Performance in reading 4-letter words versus session number at 15° eccentricity and using a viewing area containing 286 pixels. The solid line indicates the best fit to the data.

about 23% of the words, whereas subject AR identified only 6% of words. Both progressed over time. During final sessions, subject EO achieved scores of about 85% correctly read words, and subject AR scores of about 64% correctly read words. EO's scores asymptoted for the last 15 sessions, while AR's scores never reached a clear asymptote. It should however be noted that EO was tested in binocular condition and AR in monocular condition. Although overall improvements were similar for both of them, these differences in absolute scores as well as in the learning curve might thus reflect a binocular advantage.

A second experimental observation consistent with a learning process appears in the analysis of the mean response time (Fig. 9). During initial sessions, typical response times ranged between 3 and 5 s. During final sessions, typical response times decreased to 2–3 s. Experimental data were fitted to average session-to-session variability. The fits revealed that both subjects significantly reduced the mean response time as the session number increased (Pearson's correlation: $r = -0.79$, $p < 0.0001$ for EO and $r = -0.38$, $p = 0.001$ for AR). The reduction in response time was more pronounced for subject EO tested binocularly (2.4 s), than for subject AR tested monocularly (0.6 s). Interestingly, the longer initial response times of subject EO were also associated with better initial reading performances, suggesting inter-individual differences in the strategies used to perform this difficult task.

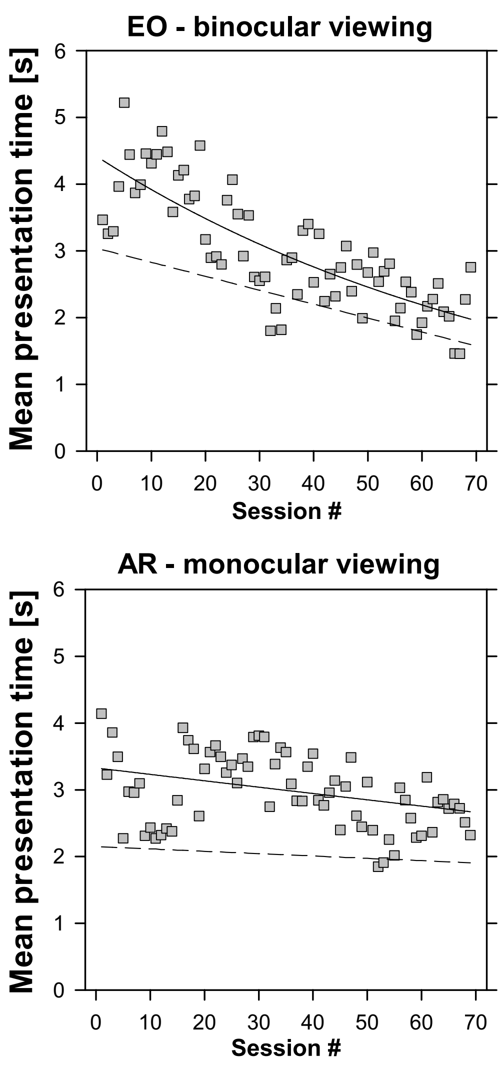

Fig. 9. Mean presentation time in reading 4-letter words versus training session number at 15° eccentricity in the lower visual field and using a viewing area containing 286 pixels. The solid lines indicate the best fits to the data. The dashed lines indicate the best fits to the data when only correct responses are taken in consideration.

This analysis, based on all, correct and incorrect responses, reflects best the effects of the global learning process, but it does occult the time subjects took to read the words they recognised correctly. An analysis based on correct responses only (dashed lines in Fig. 9) revealed that mean response times for correctly read words were generally shorter. In this case, only subject EO significantly reduced her correct response time (Pearson's correlation: $r = -0.68$, $p < 0.0001$). AR shows the same trend, but this effect is not significant on her data.

Taken together, these data clearly indicate that important improvements in performance can be obtained by training. Both subjects progressed from a poor to a relatively useful visual function during the course of this experiment. This suggests that future users of visual prostheses will need time to extract best performances from these devices, as it is the case for deaf users of cochlear implants (see e.g. Pelizzone, Cosendai, & Tinembart, 1999). It is interesting to explore in more detail some of the parameters influencing this learning process.

4.3. Influence of eccentricity and pixel number on the learning process

Fig. 10 shows the data collected using the two additional experimental conditions mentioned in the method section.

The influence of adaptation to read pixelised stimuli is demonstrated by analysing data collected using the same number of pixels, but presented via central reading (0° eccentricity). As expected from experiment 1, central reading performance of pixelised words was close to perfect for both subjects. Although both subjects slightly improved their central reading performance with time, this improvement was small relative to the overall improvements observed upon eccentric reading. Hence, the adaptation process to decipher pixelised words had only a weak influence on reading performance.

The influence of adaptation to eccentricity is demonstrated by analysing data collected at the same eccentricity (15°), but using stimuli containing 14,000 pixels

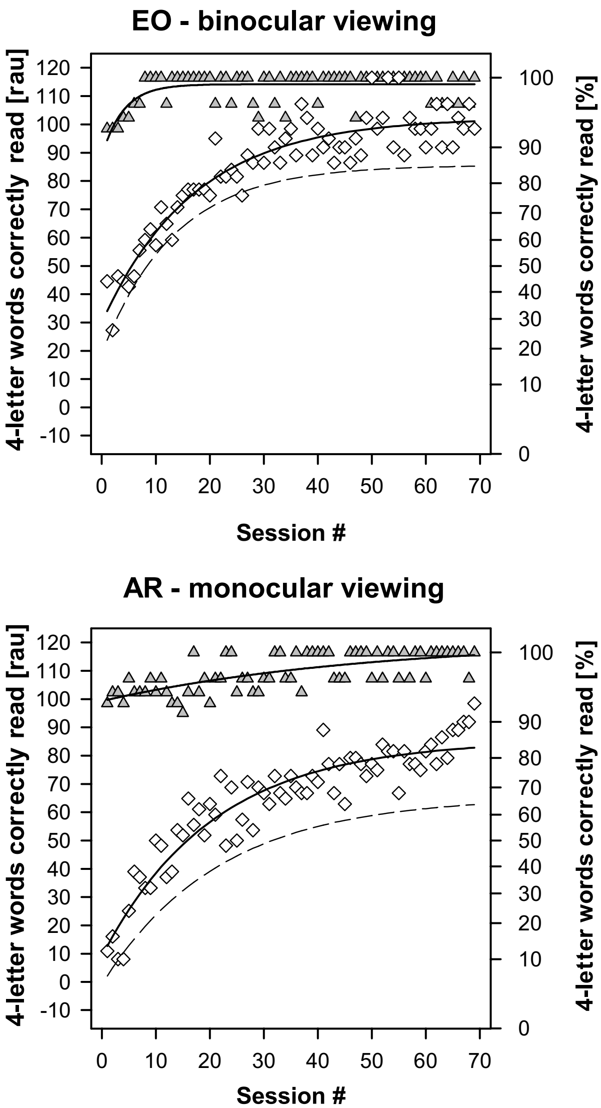

Fig. 10. Performance in reading 4-letter words versus training session number in the two control conditions: (1) in central vision using a viewing area containing 286 pixels (grey triangles), and (2) at 15° eccentricity in the lower visual field using a viewing area at maximum screen resolution (white diamonds). The solid lines indicate the best fit to the data in these two conditions. For comparison, the dashed line of the best fit to the data in the main condition is also shown.

(maximum screen resolution). For both subjects, the progression of performance over time was similar to that observed using 286 pixel stimuli. Fits to the experimental data demonstrate that the performance at maximum screen resolution is about 10%–20% higher, the effect of resolution being apparently slightly more pronounced at the end of the experiment. These results confirm that adaptation to eccentric reading was the principal component of the overall learning process.

One can conclude from these control conditions that habituation to eccentricity is presumably a dominant component in the learning process. It is interesting to note that perfect performance was never achieved at 15° eccentricity because scores collected at that eccentricity asymptoted clearly below those collected with central reading. This shows that providing more resolution can improve performance to some extent, but does not entirely compensate for the loss due to eccentricity.

4.4. Influence of familiarisation with the word set

Subjects were confronted daily for more than one month with the same finite set of 500 words. One might wonder if they improved their identification performance simply because they were progressively learning the set of possible correct answers.

We tested this issue by generating an additional pool of 200 new 4-letter words. None of the words in the new set had been used previously. Fifty word blocks were randomly extracted from this new set and presented to the subjects in testing sessions that occurred after the end of the main experiment. All other aspects of testing were exactly identical to that of the main experiment. Fig. 11 compares mean reading performances using the new word set to the data collected using the old 500 word-set throughout the experiment. For both subjects, reading performance using the new word set was significantly higher (EO: $p = 0.002$; AR: $p < 0.001$) than the performance measured at the beginning of the main experiment. Reading performance using unpractised words was only slightly lower than that reached at the end of the main experiment (EO: $p = 0.2$; AR: $p = 0.03$). This demonstrates that the benefits derived from training with one set of words could be exploited to decipher new, unpractised words.

One can conclude from this additional test that repeatedly using the same pool of words did not significantly bias our results. Thus, observed improvements over time were actually real improvements in accomplishing the demanded task. Interestingly, however, familiarisation with the word pool was important for reading speed. Indeed, pixelised words, familiar to the reader, were recognised slightly more rapidly than unpractised words presented in the same conditions.

4.5. Binocular versus monocular perceptual learning

Subject EO performed all tests using binocular vision while subject AR performed all tests in monocular vision. The final scores reached by subject EO were about 20% higher than those of subject AR (see Fig. 8). Two important questions can be raised: Is this difference reflecting an advantage of binocular vision? What would reading scores be if subjects would be asked to perform the task in the condition they did not use previously?

At the end of experiment 2, we measured on subject EO reading scores in monocular viewing condition, and on subject AR reading scores in binocular viewing condition, using the same testing conditions as in our

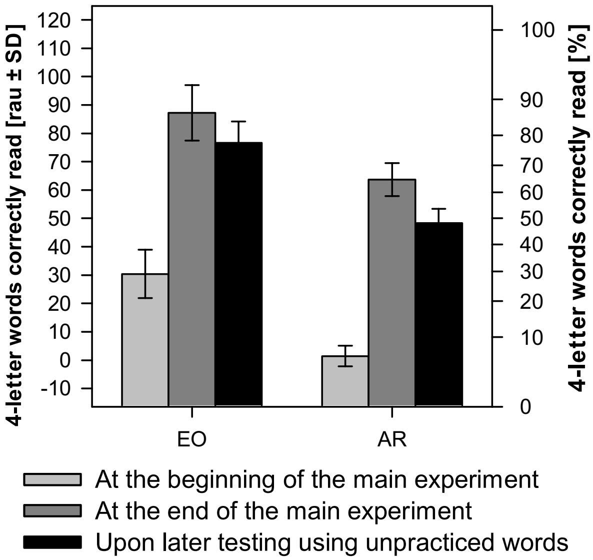

Fig. 11. Mean reading performance with unpractised 4-letter words compared to results at the beginning and the end of the main experiment. Bars indicate mean values ± SD in three conditions: (1) first three runs and (2) last three runs of the main experiment compared to (3) three additional runs with unpractised words. Experimental conditions: 15° eccentricity using a viewing area of 10° × 3.5° containing 286 pixels.

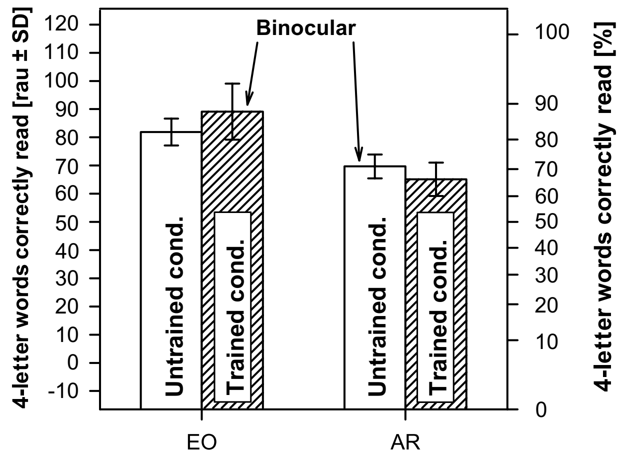

Fig. 12. Effects of using reversed viewing conditions (untrained versus trained). Bars indicate mean values ± SD. Subject EO: three additional runs in monocular condition (untrained) versus the last three runs of the main experiment in binocular condition (trained). Subject AR: three additional runs in binocular condition (untrained) versus the last three runs of the main experiment in monocular condition (trained). Experimental conditions: 15° eccentricity using a viewing area of 10° × 3.5° containing 286 pixels.

main experiment. No significant differences in reading performance were found for both subjects in such "reversed" conditions (Fig. 12). Inter-individual differences in reading scores were preserved. This indicates that the condition, in which the perceptual learning of eccentric reading was conducted, is not relevant. Training with binocular reading benefits subsequent monocular reading and, conversely, training with monocular reading benefits subsequent binocular reading There was, however, a slight, but un-significant, within-subject trend to better scores with binocular vision. This small advantage was possibly due to effects of binocular summation or inter-ocular suppression.

We were also interested to know if perceptual learning gathered with one eye transfers to the non-habituated eye. Subject AR, who did all the tests monocularly with her dominant right eye, was therefore retested using her non-dominant left eye in all three different experimental conditions. Fig. 13 shows clearly that there is no significant difference in monocular reading performance across both eyes.

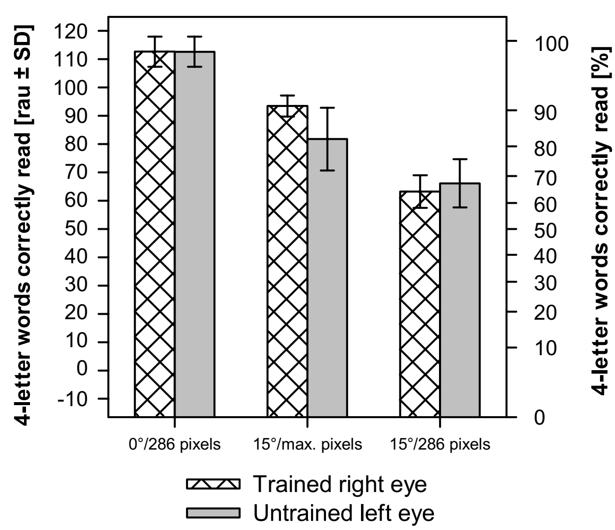

Fig. 13. Comparison of reading performances between the trained and the untrained eye at the end of the training process for subject AR. Bars indicate mean values ± SD. For each condition, the last three runs of the main experiment are compared to three additional runs conducted on the untrained eye.

4.6. Persistence of perceptual learning

Finally, we were interested to investigate if the benefits of perceptual learning of eccentric reading could persist after a significant period of non-practice.

For a 2 months period after the end of the experiments, subject EO did not participate in any testing. Her reading performance was then re-tested using the main experimental condition. Table 1 demonstrates that there was no significant change in performance after 2 months of non-practice. This indicates that perceptual learning of eccentric reading is at least preserved for a certain time.

5. Discussion

This first study was designed to explore reading performance in conditions mimicking artificial vision.

Table 1
Reading performance after two months of rest compared to the reading performance at the end of training for subject EO

Mean reading performance	4-Letter words read (EO)		
	Rau	SD	Percent
At the end of the experiment (day 36)	87.2	9.8	88.0
Two months after completion of the experiment (day 99)	85.6	1.5	85.9

Mean values are calculated on the basis of three runs: last three runs of the main experiment (day 36) and three additional runs conducted at day 99, two months after completion of the experiment. Experimental conditions: 15° eccentricity using a viewing area of 10° × 3.5° containing 286 pixels in binocular vision.

Several aspects of the experimental set-up deserve to be discussed.

We used 4-letter word stimuli, because Legge et al. (1985) initially demonstrated that this was the minimum letter-sequence allowing close to normal reading speeds. However, subsequent studies demonstrated that seeing more than 4 letters at a glance could yield better reading speeds (Beckmann & Legge, 1996; Fine, Kirschen, & Peli, 1996; Fine & Peli, 1996). Since the aim of this study was to simulate retinal implants of a relatively small area and containing a finite number of stimulation contacts, the use of a small number of letters was an advantage: (1) A small number of letters permitted to fill the restricted viewing area with large letters. The letter size is an important limiting factor if one wants to investigate eccentric reading (see also Chung et al., 1998). (2) Recent work by Thompson et al. (2000), and Dagnielie et al. (2000), demonstrated that a grid density of about 4 pixels per letter width is needed to allow for accurate character definition. This limited the number of characters that could be presented via a finite number of stimulation contacts. (3) The visual span is another important limiting factor in eccentric reading. In a recent study, Legge, Mansfield, and Chung (2001) estimated that the average visual span decreases from at least 10 letters in central vision to about 1.7 letters at 15° eccentricity, this figure however increasing somewhat with prolonged observation time. For those reasons, 4-letter word stimuli represented an adequate compromise for our experimental purpose.

We decided to conduct our experiments using a proportionally spaced font. Proportionally spaced fonts, which place letters closer together than equally spaced ones, favour the crowding effect and would therefore be less convenient for readers who are restricted to use eccentric locations of their retina. However, books, journals and most printed matters are almost exclusively printed in such proportional fonts. It was mandatory to adapt our simulations to this reality. Attempts to modify letter spacing might improve performance, as suggested by several authors (Arditi, Knoblauch, & Grunwald, 1990; Latham & Whitaker, 1996; Toet & Levi, 1992). This would however imply additional special hardware, which is too speculative to be considered at this point. Furthermore, Chung (2002) concluded a recent study, in which she used an equally spaced Courier font, with the sentence: "Increased letter spacing beyond the standard size, which presumably decreases the adverse effect of crowding, does not lead to an increase in reading speed in central or peripheral vision". Hence, the effect of letter spacing on eccentric reading is still controversial.

Finally, we used fixed text to present the stimuli. The use of different presentation methods (e.g. scrolled text or RSVP) might have increased reading speed. However, none of these methods does really mimic the use of a retinal prosthesis. Fixed text was the simplest condition to be tested and we acknowledge this limitation in our present work. More realistic experiments using full-page navigation, as well as other modes of pixelisation, are underway and will be reported soon.

Under these experimental conditions, experiment 1 clearly showed that about 300 pixels were necessary to appropriately code 4-letter words. These data replicate in part the work of Cha et al. (1992), using 4-letter words. They extend their findings, because their experiments were limited to a central visual field of 1.7°, and subjects were allowed to scan the image with eye movements. About 300 pixels appear therefore to be an intrinsic limit that is related to the type of stimulus (4-letter words) more than to the presentation protocol. Implantable microelectrode arrays consisting of about 300 active contacts seem feasible using present technology. Zrenner et al. (1997) as well as Peyman et al. (1998) have already manufactured such first prototypes. Our simulations attempted to mimic an implantable chip covering a surface of about 3×1 mm^2 on the retina with an electrode-to-electrode separation of approximately 100 μm. Multi-site stimulation measurements on chicken retinae have demonstrated that such closely spaced contacts can selectively activate retinal neurons (Stett, Barth, Weiss, Haemmerle, & Zrenner, 2000).

The amount of information that can be transmitted via about 300 stimulation contacts is however really useful only if projected onto the central part of the visual field. As our study demonstrates, reading performance drops severely at eccentricities of 10° and beyond, even if more pixels are used. At high eccentricities, the main factor limiting reading performance is not the pixel number, but the fact that only part of the information content of the stimuli can be grasped by the subject. The smallest character size we used corresponded to a visual acuity of less than 20/250. The visual acuity at eccentricities of 15°–20° is expected to be much better (Cowey & Rolls, 1974; Daniel & Whitteridge, 1961). Hence, the low performance observed at high eccentricities could not be attributed to decreased resolution in the periphery. This was confirmed by the fact that eccentric recognition of single letters was much better than eccentric reading of entire words (experiment 1). Reduced discrimination in presence of surrounding stimuli due to the so-called "crowding effect" seems to be a better explanation for low reading performance at high eccentricities.

Strictly speaking, on basis of the results collected in experiment 1, an eccentric position (>10°) of a retinal implant would strongly impair reading performance. There are however strong practical arguments suggesting that it might be required to place these implants at such high eccentricities. As already mentioned, morphological studies of the neuronal architecture of the retina, like those by Sjöstrand et al. (1999) and others, show that a direct vertical connection between photoreceptor, bipolar cells and ganglion cells is best realised in retinal areas beyond 10° eccentricity. Close to the fovea, several layers of bipolar and ganglion cells are superimposed. At up to about 10° of eccentricity, one cone may be connected to several ganglion cells, and ganglion cells are displaced radially from the photoreceptors they innervate. This distortion decreases with eccentricity. Beyond 10° of eccentricity the distortion is minimal. Such eccentric regions of the retina are therefore much better suited for retinotopic electrical stimulation. This mapping issue is of special importance for retinal implants that are designed to use in situ light falling on the retina. Such prostheses are presently developed by a German (Zrenner et al., 1999) and a US (Chow & Chow, 1997) consortium. This type of device would be the most elegant approach, if successful, but it does not really afford for pre-processing to prevent non-retinotopic mapping. If other systems using an external camera to capture the stimuli are considered, such as those envisioned in the projects of Humayun et al. (1999) or Rizzo and Wyatt (1997), the transmitting hardware could possibly include remapping routines. Although this is technically conceivable, it might require prohibitive amounts of perceptual tests for adjustment. For these reasons, we are convinced that it would be optimal to try to place a retinal implant beyond 10° of eccentricity in a first attempt.

These considerations raised the question, as to whether subjects could adapt to eccentric reading. Improvements in the accomplishment of tasks, involving stimuli presented in peripheral vision, have already been reported by several authors to be task-specific. For example, learning has been observed for vernier acuity and bisection, for stereoscopic orientation and time discrimination tasks, but not for resolution tasks or Landolt C acuities (e.g. Beard, Levi, & Reich, 1995; Crist, Kapadia, Westheimer, & Gilbert, 1997; Schoups, Vogels, & Orban, 1995; Westheimer, 2001). Taken together these findings imply that spatial visual functions, which rely on important processing in higher cortical areas, can be improved by training in the visual periphery. In particular the "crowding effect" seems to be of cortical and not of retinal origin (e.g. Levi, Klein, & Aitsebaomo, 1985). Electrophysiological experiments in the monkey, monitoring the functional properties of the primary visual cortex area V1, suggest that perceptual learning is accompanied by a decrease of the "crowding effect" (Crist, Li, & Gilbert, 2001). Moreover, a paper by Leat, Li, and Epp (1999) states that the "crowding effect" also includes an important component of attention; [8] this component being potentially improved by training, as indicated by experiments on contour interaction (Manny, Fern, Loshin, & Marinez, 1988) or visual search (e.g. Sireteanu & Rettenbach, 1995, 2000). There is also extensive evidence in the low vision literature that educational training (e.g. in the use of optical aids) is an important factor for successful eccentric reading by patients with macular scotoma (see e.g. Peli, 1986). In some cases, greatly improved reading capacities were already observed with as little as about 5 h of training (Nilsson, 1990). However, the conditions encountered by low vision patients are markedly different from those expected from users of retinal implants. Low vision patients are generally able to use large parts of their retina, situated relatively close to the fovea, while the stimuli used in this study were restricted to a small area, stabilised at a high eccentricity in the lower visual field and pixelised. It was therefore important to test if training could improve performance in conditions mimicking retinal implants.

Experiment 2 was especially designed to investigate if eccentric reading, under conditions simulating a retinal implant, could be improved by learning or if it would be limited by fundamental properties of the visual system. The two subjects tested in this study, demonstrated clearly that they were able to adapt, and their performance improved impressively over time. While more subjects would be needed to better quantify the average amount of improvements that can be expected, two subject were sufficient to demonstrate the existence of learning. Control measurements revealed that this type of learning: (1) was not an artefact due to the progressive memorisation of the set of possible answers, and (2) it was not specific to the trained eye and could be transferred to the untrained eye. This latter finding is in contrast to observations for which learning was restricted to the trained condition, with little or no transfer to the non-trained aspects of the stimulus or to the other eye (Karni & Sagi, 1991; Poggio, Fahle, & Edelman, 1992). Complete interocular transfer, as observed here, favours perceptual learning mechanisms occurring in higher-order, binocular areas, as for

[8] Attention, when directed towards the eccentric retinal locus, reduces attentional effects of crowding.

example suggested for motion direction discrimination (e.g. Ball & Sekuler, 1987; Schoups et al., 1995; Schoups & Orban, 1996). An alternative explanation might be the involvement of high-level attentional or other cognitive mechanisms, which modulate the specific levels of early visual processing, as suggested by Ahissar and Hochstein (1993, 1996) or Beard et al. (1995). We also found that perceptual learning of eccentric reading was at least maintained for a period of two months after completion of the training. Persistence of perceptual learning over periods of several months has been found, for example by Fiorentini and Berardi (1981) in grating waveform discrimination, by Ball, Beard, Roenker, Miller, and Griggs (1988) or Sireteanu and Rettenbach (2000) for visual search tasks, or by Beard et al. (1995) for vernier and resolution acuity.

On the basis of the present study, it is not possible to determine the importance of the different factors influencing on the learning process. Are better performances mainly due to a better control of undesirable reflexive eye movements during the experiments, or are they due to a decrease in the "crowding effect"? Both effects are probably in close relation. Preliminary results on full-page text reading under conditions simulating an eccentric retinal implant indicate that the suppression of undesirable reflexive eye movements plays a dominant role in the learning process.

6. Conclusion

Based on these results, it appears that functional retinal implants with a few hundred stimulation contacts might successfully restore some reading abilities to blind patients, even if placed outside the fovea. Optimal performance with such devices will however require a significant adaptation process. As future users of retinal implants will have to wear their prosthesis permanently, we expect them to benefit even more from adaptation than the normal subjects in our simulation experiment. Our present results are in this respect very encouraging for the future.

Additional research on eccentric reading of whole page texts in similar conditions is required, as well as studies focusing on other important visual tasks such as spatial orientation (mobility) and spatial localisation (visuo-motor coordination), to get a more complete picture of the potential benefits that could be derived from retinal prostheses.

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