Processes Involved in Oculomotor Adaptation to Eccentric Reading

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PURPOSE. Adaptation to eccentric viewing in subjects with a central scotoma remains poorly understood. The purpose of this study was to analyze the adaptation stages of oculomotor control to forced eccentric reading in normal subjects.

METHODS. Three normal adults (25.7 ± 3.8 years of age) were trained to read full-page texts using a restricted 10° × 7° viewing window stabilized at 15° eccentricity (lower visual field). Gaze position was recorded throughout the training period (1 hour per day for approximately 6 weeks).

RESULTS. In the first sessions, eye movements appeared inappropriate for reading, mainly consisting of reflexive vertical (foveating) saccades. In early adaptation phases, both vertical saccade count and amplitude dramatically decreased. Horizontal saccade frequency increased in the first experimental sessions, then slowly decreased after 7 to 15 sessions. Amplitude of horizontal saccades increased with training. Gradually, accurate line jumps appeared, the proportion of progressive saccades increased, and the proportion of regressive saccades decreased. At the end of the learning process, eye movements mainly consisted of horizontal progressions, line jumps, and a few horizontal regressions.

CONCLUSIONS. Two main adaptation phases were distinguished: a “faster” vertical process aimed at suppressing reflexive foveation and a “slower” restructuring of the horizontal eye movement pattern. The vertical phase consisted of a rapid reduction in the number of vertical saccades and a rapid but more progressive adjustment of remaining vertical saccades. The horizontal phase involved the amplitude adjustment of horizontal saccades (mainly progressions) to the text presented and the reduction of regressions required. (Invest Ophthalmol Vis Sci. 2006;47:1439–1447) DOI:10.1167/iovs.05-0973

In humans, selective attention is mainly focused around the fovea, the retinal area providing the highest spatial resolution. The oculomotor system is constructed essentially to subserve foveal function by directing and stabilizing images of interest to that retinal location. When the fovea is lost as a result of disease, affected subjects strive to use optimally spared retinal areas as a replacement. Adaptation to this viewing condition may involve several processes. Sparred retinal areas with best visual acuity and/or appropriate visual field (“visual span”) should be identified. Such eccentric retinal locations are commonly known as preferred retinal loci (PRL).1,2 Selective attention must be transferred to these eccentrically located PRL.3 In addition, oculomotor control mechanisms should be reorganized to allow shifting images of interest directly to the PRL.4 There is no simple rule by which patients select a particular PRL,3,5 but it appears that PRL location can be influenced by several factors (e.g., attentional1,7). Multiple PRL with specific complementary functions can be used in combination.8–14

The development of eccentric fixation seems to appear before the ability to perform saccades shifting the image of interest onto that new fixation area. An experimental study where bilateral foveal lesions were made in three adult monkeys showed that while both fixation and saccadic mechanisms may adapt to foveal loss, saccadic adaptation requires a much lengthier process.4 In that experiment, eccentric fixation occurred as early as 1 day after the lesion, and new PRL stabilized within 2 days. In contrast, numerous reflexive saccades inappropriately projecting visual stimuli onto the damaged fovea were still observed the first days after the lesion. Saccades gradually adapted to reference the newly developed PRL over a period that lasted several weeks. Two months after the lesions were induced, two of the three animals were able to generate saccades, bringing the PRL directly or close to the target image. In a clinical report of a patient who had the sudden development of a large central scotoma, the first stages of oculomotor adaptation to the field defect have been analyzed.15 Impressively, target fixation attempts evolved from large, apparently poorly controlled saccades to small, mainly horizontal saccades centered on defined retinal areas in a rapid (<20 seconds) and structured process. In another clinical study involving patients with central field defects, various re-fixation strategies were identified.16 One of these patients had a central monococular scotoma and therefore presumably had not used his affected eye for fixation. With that eye, he showed a striking foveating-defoveating strategy: to fixate a stimulus appearing in the peripheral visual field, he first performed a foveating saccade (inappropriately projecting the target image onto the central scotoma) and subsequently generated an additional saccade projecting the image onto the PRL. This distinction between the development of eccentric fixation and the adaptation of eccentric (non-foveating) saccades suggests that oculomotor adaptation to peripheral viewing relies on multiple mechanisms.

In our laboratory, we are conducting a series of psychological experiments to determine, for a variety of tasks, the minimum requirements for a retinal prosthesis to restore useful artificial vision to blind patients. In this context, we recently published a study17 focusing on full-page text reading. Tested subjects were requested to read entire pages of text presented on a computer screen, using a restricted viewing area that was stabilized at a defined, first central and then eccentric visual field location. After systematic training, useful reading was achieved with a viewing area stabilized at high eccentricity. Our paper focused on issues essential to the development of visual prostheses, and most of the data collected on the ocular motor adaptation process are not reported. These results,
however, also offer a unique opportunity to study the overall process through which subjects adapt to eccentric viewing. In the present study we further analyze these data, to better define the processes of oculomotor adaptation to eccentric reading. To our knowledge, this is the first attempt at describing such processes in human subjects.

The restricted and stabilized viewing area used in our experiments can be considered an artificial, suddenly imposed PRL. In this setting, we found that one of the main issues involved in the learning process was the adjustment of oculomotor control, to reference as accurately as possible the eccentric viewing area used to navigate across text pages. We observed that the adaptation of eye movements includes several distinct processes. This analysis is presented herein.

METHODS

Subjects
Three normal subjects (AD, DV, and DS; respective ages: 23, 24, and 30 years) participated in the study. All of them were native French speakers, naive to the task but familiar with the purpose of the experiment. They had normal ophthalmic status and normal or corrected to normal visual acuity. The experiments were designed according to the guidelines of the Declaration of Helsinki and were approved by the local ethical authorities.

Experimental Procedure
Stimuli consisted of full pages of text presented to the subjects in bitmap image format. A pool of 100 articles was downloaded from the Internet Web site of the popular Swiss newspaper Le Temps (http://www.letemps.ch). Each article was divided in 10 text segments, each containing seven lines of text (~25 words). The Arial font was used and the height of the lowercase letter x was 1.8° at a 57-cm viewing distance. These text segments were transformed to bitmap images and processed (pixelized) with commercial software (Photoshop ver. 5.5; Adobe, Mountain View, CA). Figure 1 displays an example of such a text.

Subjects sat in front of a 22-in. screen, at a viewing distance of 57 cm. In each experimental session, subjects were requested to read the first four pages of a newspaper article displayed on the screen. The text page was visible only through a 10° × 7° rectangular viewing area, stabilized at a determined location of the visual field. Stabilization of the viewing window on the retina was achieved by online gaze position compensation. Eye movements were monitored with a fast video-based eye and head-tracking system (SMI EyeLink; SensoMotoric Instruments GmbH, Teltow/Berlin, Germany). A photograph of one of the subjects sitting in front of the stimulation screen and wearing the eye-tracking system is shown in Figure 2a. Gaze position data captured by the eye-tracking system were used to move the viewing window with respect to the page of text and to update its contents accordingly (see Fig. 2b). The maximum delay between the actual eye movement and the subsequent update of the position and content of the viewing window was 14 ms. The viewing window contained 572 pixels (minimum information content required for useful reading), and at least four characters were visible inside it at a glance (minimum required for efficient reading).

In the first phase of the experiment, the center of the viewing window was stabilized on the fovea. Once subject became accustomed to the experimental setup and reached stable reading performances (i.e., after 8 to 16 experimental sessions) the training period for eccentric reading began. For this second phase, the center of the viewing window was stabilized at 15° eccentricity in the lower visual field. Two experimental sessions were conducted each working day of the week. An experimental session never lasted more than 30 minutes, to avoid fatiguing the subject, resulting thus in approximately 1 h/day

FIGURE 1. Example of a pixelized full-page text. Hyphenation was used to maximize words and texts were not justified. The image covered the whole screen, subtending a visual angle of 40° × 30°.

FIGURE 2. Experimental setup. (a) A tested subject is wearing the head-mounted eye tracker. (b) Illustration of the screen as viewed by the subject during an experimental session. The page of text was only visible through a 10° × 7° viewing window that shifted to follow the subject’s eye movements (arrows). This window was stabilized either in central vision or at 15° eccentricity in the lower visual field (as shown in the illustration). Please note that the cross marking of the foveal fixation point is only schematic (there was no foveal fixation point present during the task).
of training. Experiments stopped once reading scores became asymptotic (between 55 and 68 sessions). Tests were performed monocularly, with the dominant eye. Eye movements were recorded throughout the experiment and stored for further analysis.

Please refer to our previous papers for more details on the experimental setup and procedure.

**Data Analysis and Statistics**

Saccades detected online by the automatic parser of the eye-tracking system were analyzed to define the various stages of the oculomotor adaptation process for eccentric reading. For a saccade to be detected by the system, several criteria had to be fulfilled: a minimum eye displacement of 0.1°, a velocity threshold of at least 30 deg/s, and a minimum acceleration threshold of 8000 deg/s².

Detected saccades were categorized into three main groups according to their orientation (Fig. 3a): horizontal saccades (those with an angle of ±20° around the horizontal axis, and directed either right or left), vertical saccades (those with angles between 70° and 110° around the vertical axis, and directed either up or down), and oblique saccades (those not fitting into any of the preceding categories). Horizontal saccades were further subcategorized (Fig. 3b) into progressions (horizontal saccades directed right and <10° in amplitude), regressions (horizontal saccades directed left and <10° in amplitude), and line jumps (horizontal saccades directed left and >20° in amplitude).

Saccade frequency was calculated as the total number of saccades performed during an experimental session (i.e., four full pages of text). Saccade amplitude was computed as the total absolute eye displacement (length) between the eye position at the beginning of the saccade and its end position. Average saccade amplitude for a given experimental session was calculated on the basis of the absolute amplitude of all saccades performed during the session.

Significant changes in oculomotor behavior throughout the learning process were determined with Pearson’s correlation (linear regression). In addition, whenever the results allowed it, we computed learning curves to average intersession variability and better highlight the time course of the learning process. These learning curves were obtained by fitting the data to an exponential function. Stabilization times were determined based on the exponential time constant (τ), which corresponds to the time required for the function to vary by a factor of 1/e (approximately 0.368). The stabilization time of an exponential function is generally estimated as 3τ.

**RESULTS**

When using central vision, performance increased and stabilized after 8 to 16 experimental sessions. Detailed reading performance results have already been reported in our previous paper. Briefly, when using central vision, initial reading scores were already higher than 95%. Reading rates increased from 60 to 70 words per minute to stabilize at approximately 72 to 122 words per minute. For eccentric reading, two subjects (DV and DS) started the experiment with reading scores that were nearly 13% correct and reached final scores between 86% to 98% correct. Subject AD, who had already attained good scores (>85% correct) in the first sessions, achieved final scores higher than 98% correct. Reading rates improved impressively: from 5 to 26 words per minute for subject AD, from 3 to 14 words per minute for subject DV, and from 1 to 28 words per minute for subject DS.

Samples of successive gaze position recordings obtained during a choice of experimental sessions, superimposed to the corresponding text page presented, are displayed in Figures 4 (central reading) and 5 (eccentric reading).

During the first training sessions for eccentric reading, oculomotor behavior appeared quite inappropriate for the reading task: large vertical saccades predominated. Subjects seemed unable to fixate presented words or to follow a line of text. Oculomotor behavior evolved gradually. Eye movements intended to decipher single words were already visible as early as in the 5th session, especially for subject DV. At the end of the training period, all subjects developed a structured page navigation strategy.

When comparing final eccentric reading strategies with those observed by the end of the previous central vision reading tasks (compare Figs. 4, 5), it appears that, after training, both eye movement patterns were roughly similar. The viewing window focused on consecutive words and across successive lines of text. Forward-directed saccades shifting fixation from one word to the next (progressions) and saccades shifting fixation from the end of one line to the beginning of the next (line jumps) were clearly distinguishable. Occasionally, subjects traced back on the same line (regressions), to visualize specific words again. However, differences could also be noted between central and eccentric reading. In eccentric vision,
regressions occurred more frequently. Moreover, horizontal
saccades seemed less precise; therefore, more small corrective
saccades were required.

These considerations were based on a qualitative assess-
ment of the oculomotor adaptation process observed in
our subjects. To provide an objective evaluation of the changes
that occurred in the reading strategy, a quantified analysis of
our data was conducted. The characteristics of the recorded
saccades will be described in the following section.

Saccadic Adaptation

The distribution of saccades performed during the 1st, 5th,
15th, and last eccentric reading sessions is plotted in Figure 6.
During the first training session, bundles of large vertical sac-
cades were observed. Many of these eye movements were
between 10° and 20° in amplitude, probably reflecting recur-
ring (reflexive) attempts to bring the stimulus image onto the
fovea (foveating saccades), followed by an equivalent saccade
of opposite direction attempting to bring the viewing window
back on the stimulation screen. In the fifth session, these
movements were no longer visible in subjects AD and DV, and
only a few of them were still observed in subject DS. The
remaining vertical saccades gradually decreased in amplitude,
to become hardly visible at the end of training. In contrast,
structured patterns of horizontal eye movements developed in
the 5th session in two subjects (AD and DV). From the 15th
session on, horizontal saccades predominated over the initially
prevailing vertical pattern. In the last training session, eye
movements essentially consisted of progressions, regressions,
line jumps, and other small corrective saccades.

Changes in saccade counts (frequencies) by category, are
plotted in Figure 7. The total number of vertical saccades
decreased significantly over time in all subjects (Pearson’s
correlation: \( r = 0.58, P < 0.0001 \) for AD; \( r = 0.39, P < 0.01 \)
for DV; and \( r = 0.72, P < 0.0001 \) for DS). An approximate
15-fold drop was observed after 3, 20, and 25 sessions in subjects
DV, AD, and DS, respectively. Slighter (approximately
5-fold) but significant (Pearson’s correlation: \( r = 0.72, P < 0.0001 \)
for AD; \( r = 0.73, P < 0.0001 \) for DV; and \( r = 0.82, P < 0.0001 \)
for DS) frequency decays were observed for oblique
saccades. In subjects AD and DS, the process was slower (35
and 38 sessions, respectively) than for vertical saccades. In
subject DV, values were still decreasing when the experiment
ended. Evolution of horizontal saccade counts was more com-
plex, and data could not be fitted with an exponential curve. In
AD and DV, these increased significantly during the first 15
sessions (respectively, Pearson’s correlation: \( r = 0.60, P < 0.05 \)
and \( r = 0.72, P < 0.01 \)) and then significantly decreased
(respectively, Pearson’s correlation: \( r = 0.48, P < 0.001 \) and
\( r = 0.31, P < 0.05 \)). In subject DS, horizontal saccade counts
increased significantly during the first seven sessions (Pear-
son’s correlation: \( r = 0.91, P < 0.01 \)) and then decreased
significantly (Pearson’s correlation: \( r = 0.82, P < 0.0001 \)).

Additional results were obtained after horizontal saccade
subcategorization (Fig. 8). The proportion of progressions in-
creased significantly in all three subjects, from average values
ranging between 45% and 60% in the first sessions up to
approximately 65% by the end of training (Pearson’s correla-
tion: \( r = 0.74, P < 0.0001 \) for AD; \( r = 0.45, P < 0.001 \) for DV;
and \( r = 0.74, P < 0.0001 \) for DS). Only subject AD reached an
asymptote (after 50 sessions). Regressions behaved inversely.
In the beginning of training, they represented approximately
41%, 34%, and 43% of the total number of horizontal saccades
in AD, DV, and DS, respectively. These proportions signifi-
cantly decreased to 17%, 26%, and 27%, respectively (Pearson’s
correlation: \( r = 0.70, P < 0.0001 \) for AD; \( r = 0.65, P < 0.0001 \)
for DV; and \( r = 0.81, P < 0.001 \) for DS). At the end of the
experiment, the proportion of regressions was still decreasing
in subjects DV and DS, whereas in subject AD, values stabilized
after approximately 30 sessions. The total number of line
jumps increased significantly with training in DV and DS (Pear-
son’s correlation: \( r = 0.64, P < 0.0001 \) and \( r = 0.61, P < 0.0001 \),
respectively). Line jump counts in AD were more variable,
but also tended to increase over time (Pearson’s correlation:
\( r = 0.20, P = 0.1 \)). Values in subjects AD and DV stabilized after
approximately 16 and 27 sessions. In the case of subject DS, line jump counts had not reached an asymptote
when the experiment ended.

Average amplitude of the different saccade categories was
also modulated throughout the training period (Fig. 9). For
vertical saccades, amplitudes dropped significantly from initial
values of 5° to 8° down to final values of around 3° (Pearson’s
correlation: \( r = 0.56, P < 0.0001 \) for AD; \( r = 0.69, P < 0.0001 \)
for DV; and \( r = 0.72, P < 0.0001 \) for DS). Asymptotes were
reached after 13, 20, and 27 sessions in subjects DV, AD, and
DS, respectively. Average amplitude of oblique saccades re-
mained stable in subject DS, and decreased very slightly but
significantly in subjects AD and DV (respectively, Pearson’s
correlation: \( r = 0.34, P < 0.01 \) and \( r = 0.47, P < 0.0001 \)). In con-
trast, average amplitude of horizontal saccades significantly
increased from values ranging between 5°, 4°, and 2.5°, up to
7°, 6°, and 4° in subjects AD, DV, and DS (correspondingly,
Pearson’s correlation: \( r = 0.42, P < 0.001 \); \( r = 0.51, P < 0.001 \);
and \( r = 0.80, P < 0.0001 \)). In subject DS, amplitudes did not
stabilize, whereas in subjects AD and DV, curves reached
asymptote after 20 and 25 sessions, respectively.

Discussion

Eccentric vision requires adaptation of oculomotor control to
such specific viewing conditions. Reflexive foveating mecha-
nisms must be suppressed and saccadic eye movements must be redirected to the new fixation locus.

Our data demonstrate that the pattern of eye movements changed impressively throughout the learning process. Certain oculomotor adaptation stages appeared consistently in all tested subjects. Two essential adaptation processes were distinguishable: a faster, vertical phase aimed at suppressing reflexive foveation, and a slower, horizontal phase dedicated to the restructuring of the horizontal eye-movement pattern.

During the first sessions, numerous vertical foveating saccades were observed. Interestingly, the first rapid, vertical adaptation process appeared to include two relatively distinct, parallel phases: one consisting of the reduction of the vertical saccade count, the second of the reduction of both the oblique saccade count and vertical saccade amplitude. According to our results, the former occurred promptly, and the latter, although rapid, was more progressive. It is reasonable to presume that both aim at reducing reflexive foveation, but each relies on distinct mechanisms, as suggested by their different time course.

The second, slower adaptation phase concerned the restructuring of the horizontal eye movement pattern. In the initial sessions, no structured reading sequence was distinguishable. Frequency of horizontal saccades increased during the first 7 to 15 sessions and then slowly decreased, whereas their average amplitude increased all through the learning process. The proportion of progressions increased gradually. It has been demonstrated that, in eccentric vision, the visual span

\[\begin{align*}
\text{AD} & \quad \text{DV} & \quad \text{DS} \\
1^\text{st} & \quad \text{C'est une boîte noire accrochée au mur. Avec un coude de poche, le prof peut facilement y voir une ampoule, allumant au centre d'un fourreau carré...} & \quad \text{Face au sida, les autorités sanitaires occidentales procèdent à la vaccination est inéparable d'une bonne prise en charge de la maladie. Comment en effet...} & \quad \text{...dé pour mener une enquête sur l'effet de ces munitions dans le Golfe et les Balkans. Elle vient de lancer un appel de fonds pour 2 millions de...}

5^\text{th} & \quad \text{André Demaurex, l'homme qui dirige depuis près de trente ans le collège lausannois du Bevo-dère, prendra sa retraite à la fin de l'année scolaire. Une retraite...} & \quad \text{...départ. Rien ne dit qu'il permettra d'assurer le bon fonctionnement d'une Union européenne forte de 27 membres à l'horizon 2010. Le teint blafard après quatre...} & \quad \text{...la terreur qu'inspire la fraude du dentiste est peut-être sur le point de devenir un mauvais souvenir. Grâce à l'action de certaines molécules, les dents pourraient un...}

15^\text{th} & \quad \text{"Vous n'avez pas devant vous un O.C.I. mais un Schmul!" C'est en ces termes que le nouveau conseiller fédéral s'est adressé à son groupe...} & \quad \text{...répond également à sa faculté d'être d'ici et d'ailleurs. Sandoz a beaucoup voyagé, et jeune, pour briser des carcans et des habitudes. Illuminé autrefois par des...} & \quad \text{...lors de l'élection de la Constituante, l'UDC a gagné deux sièges en obtenant 10 fauteuils sur 130. Mais, davantage que le nombre, c'est la composition de la...}

\text{Last} & \quad \text{...qui en sont atteints une survie inespérée il y a encore quelques années. Cette survie est toutefois réservée à une petite minorité de patients. Pour les 25...} & \quad \text{...équivalent. Un art délicat : il ne suffit pas d'enrober quelques milligrammes de principe actif dans une poudre de pertinipin ou de les dissoudre dans un...} & \quad \text{...ministre de l'Agriculture et de la Protection des consommateurs, aurait ainsi pu déclencher un soulèvement paysan dans une Allemagne traumatisée...}
\end{align*}\]

\text{FIGURE 5. Gaze position recorded for the three normal subjects during the 1st, 5th, 15th, and last eccentric reading sessions. Solid line: trajectory of the center of the viewing window relative to the text (see Fig. 2b).}
can increase with training. This should result in fewer but longer saccades, as observed in our data. A significant reduction in the proportion of regressive saccades was also observed in all subjects. As a rule, when reading difficulty decreases, saccade length increases, and the frequency of regressions diminishes. Subjects spontaneously reported that the task became easier with training, resulting in better word recognition during eccentric fixation (see also our previous publications). Thus, fewer regressions were necessary for deciphering. Line jumps developed gradually, and better calibration of progressive saccades was achieved with training. Hence, as better eccentric oculomotor control was developed, fewer corrective saccades were needed. Two parallel, presumably related phenomena may therefore be distinguished during the development of horizontal saccade control. The first one corresponded to the adaptation of the amplitude of horizontal saccades (mainly progressions) to the text presented. The second one consisted of the reduction in number of regressions.

Our results showed that, even when optimal eccentric reading performance has been attained, oculomotor behavior was not optimal compared with that observed in central vision (compare results for central and eccentric reading in Figs. 7, 8, 9). Although subjects adapted to the eccentric reading task,
vertical saccades did not disappear completely. More horizontal and oblique saccades were necessary in eccentric vision than in central vision. In two of the three subjects, more line jumps were performed and horizontal saccades were smaller during eccentric reading. In general, oblique saccades were smaller for eccentric than central viewing conditions. These results clearly demonstrate that, even after extensive training, the characteristics of saccades performed during eccentric and central reading differed. A previous investigation in patients with central scotoma described similar behavior. Even when these patients had adapted to direct images consistently onto the PRL, characteristics of eccentric saccades differed from those of foveating saccades. Typically, foveating saccades have shorter latencies and are more accurate than eccentric, nonfoveating saccades. Taken together, these findings confirm that subjects suppress foveating saccades and then adapt nonfoveating saccades to reference the new fixation locus, in accordance with previous reports.

Limitations and Implications of the Present Study

Our experimental setting obviously does not fully simulate the functional constraints and remaining retinal capacities found in conditions associated with central scotomas and eccentric reading. Furthermore, the results presented herein were certainly influenced by the artificial constraints imposed by our experimental setting.

Unlike most patients with macular disease, our subjects were also confronted with artificial tunnel-vision conditions. As a consequence, page navigation was not only limited by eccentric viewing, but also, because of the lack of peripheral information (restricted by the size of the viewing window). It is therefore possible that subjects learned to make stereotyped patterns of horizontal forward and return saccades to move the viewing window along the text. Another possibility is that subjects achieved horizontal page navigation by performing saccades to “meaningful” portions of the text that were already visible in the viewing window. Both strategies limit the amplitude and timing of the resultant eye movements, therefore restricting the maximum reading speed that the subjects attained. Furthermore, patients with central scotoma can develop multiple PRL that may be used in combination to improve reading performance, whereas, in our experimental setting, subjects had to cope with a single and fixed PRL.

The retinal location of our artificial PRL and the choice of the task to be performed (reading) also influenced the oculomotor adaptation pattern. The orientation of foveating saccades obviously depends on the absolute position of the restricted viewing window relative to the fovea. In our case,

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**FIGURE 7.** Changes in saccade frequency versus session number for the three subjects during training of eccentric reading, by saccade category. Average values in central vision (black dashed lines) are also shown for comparison.

**FIGURE 8.** Evolution of the different horizontal saccade subcategories versus session number for the three subjects during training of eccentric reading. The proportions (%) of progressions and regressions were calculated on the basis of the total number of horizontal saccades. Average values in central vision (black dashed lines) are also shown for comparison.
foveating saccades were vertical because the restricted viewing window was stabilized at a given position along the vertical meridian. Furthermore, for this reading task, the page navigation strategy essentially consisted of horizontal saccades (saccades performed from one word to the next, and from the end of one line to the beginning of another). Therefore, because of the nature and requirements of the task, subjects essentially optimized the horizontal oculomotor pattern once foveating saccades were controlled. Moreover, Peli\textsuperscript{27} suggested that an orthogonal paradigm (where eccentricity direction is perpendicular to direction of gaze or target movement), as used in our experiments, might favor eccentric oculomotor adaptation.

Despite these methodological limitations, our experimental setting simulated the fundamental constraints faced by patients with central scotoma. In these patients, at least one new fixation locus must be developed to compensate for the missing fovea, and eye movements should be recalibrated accordingly. We therefore believe the present results offer useful indications of how mechanisms for eccentric reading are constructed, at least in certain circumstances.

Additional Considerations

Even after extensive training, eccentric reading remained a difficult task resulting in low reading rates, as consistently observed in clinical practice.\textsuperscript{6,19,20} As already discussed, suboptimal control of eccentric, non-foveating saccades might limit the maximum reading performance that can be achieved in eccentric viewing conditions. However, optimal peripheral reading rates were approximately five times slower than those obtained by the same subjects in the initial central viewing experiments. Oculomotor deficits observed at the end of training can hardly account for such a slowdown. Previous research\textsuperscript{18,26–50} demonstrated that peripheral reading remains slow, even when no eye movements are necessary (i.e., the RSVP paradigm). Similar to these investigations, in our experiments, maximum reading rates were essentially limited because of the spatial constraint of the viewing area. Such visual span restrictions are known to be even more important in peripheral than in central vision.\textsuperscript{17,31,32} Other possible factors have already been discussed in our companion publication.\textsuperscript{17}

When considering the analysis reported herein, together with the reading performance results reported in our previous paper,\textsuperscript{17} no consistent correlation could be established between reading performance and the course of oculomotor adaptation to eccentric reading. Furthermore, significant learning effects have been demonstrated in previous eccentric reading studies\textsuperscript{18,20} where page navigation (i.e., the development of precise eccentric oculomotor control) was not required. This suggests the existence of additional adaptation mechanisms that were difficult to analyze in this study, such as learning to shift attention from the foveal region toward the eccentric retinal area stimulated.\textsuperscript{5,7}

The learning effects reported in this article, altogether with those described in our companion publication,\textsuperscript{17} might appear surprising because experiments were performed in normal subjects interleaving short eccentric viewing sessions with much longer periods of normal foveal viewing. Similar learning effects, however, have also been reported elsewhere.\textsuperscript{18,53} One possibility is that learning effects acquired within a single experimental session are somehow retained in the next one. Another explanation could be that learning results from some kind of perceptual assimilation occurring between sessions. Our experience suggests us that it could be a combination of both. This issue would be an interesting line of investigation for future research efforts.

In conclusion, our results demonstrate that oculomotor adaptation to eccentric reading involves at least two parallel processes: a faster suppression of the mechanisms generating reflexive foveating saccades and a lengthier process aimed at optimizing the remaining saccades (especially in the horizontal plane in the case of reading). Even after systematic training, eccentric reading remains a difficult task resulting in low reading rates.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Changes in average saccade amplitude (in degrees) versus session number for the three subjects during training of eccentric reading, by saccade category. Average values for central vision (black dashed lines) are also shown for comparison.}
\end{figure}

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