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ABSTRACT

Background: Reading with a central scotoma involves the use of preferred retinal loci (PRLs) that enables both letter resolution and global viewing of word. Spontaneously-developed PRLs however often privilege spatial resolution and, as a result, visual span is commonly limited by the position of the scotoma. In this study we evaluated a training procedure aimed at improving oculomotor behaviour in subjects with major reading difficulties related to limited global viewing capacity.

Methods: Five subjects were enrolled. They showed stable maculopathy and persisting major reading difficulties despite previous orthoptic rehabilitation. They underwent ten training sessions using the scanning laser ophthalmoscope (SLO), where they had to read single letters and isolated words varying in length, by combining the use of their initial PRL with the one of an examiner’s selected trained retinal locus (TRL). ETDRS visual acuity, threshold character size for single letters and isolated words, eye movements and reading strategies were evaluated before, immediately after SLO training, and three months later. Reading strategies were analysed from SLO recordings using a pattern-matching computer software and were related to functional changes.

Results: Subjects benefited from the training procedure both immediately after SLO training and three months later. The training firstly contributed to adapt oculomotor strategies. Immediately after SLO training, subjects used in combination with their initial PRL, the examiner’s selected TRL and other newly self-selected PRLs. Secondly, training gains were also reflected in ETDRS acuity and threshold character size for words of different lengths. ETDRS acuity and threshold character size for single letters improved significantly over training. Interestingly, subjects benefited differently from the training procedure and gains were retained differently as a function of word length.
**Conclusions:** The acquisition of newly self-selected PRLs and new oculomotor patterns suggests that the structured training procedure that aimed primarily at developing an examiner’s selected TRL, initiated in fact a more global functional adaptation process. As already suggested in neuro-rehabilitation studies, training might trigger general changes in adaptation strategies, which could “prime” the brain for future learning.

**INTRODUCTION**

Loss of reading ability is a leading complaint of subjects with central scotomas due to macular disorders, such as age-related macular degeneration (AMD) [e.g. 1, 2]. As fixation frequently shifts to a non-foveal location, an adaptation of the oculomotor system is necessary to search for, position and stabilise visual targets [3]. During such an adaptation, individuals develop one or several eccentric locations in the visual field that enable them to achieve fixation and reading [1, 3-11]. These eccentric locations are referred to as preferred retinal loci (PRL) [9]. Eccentric PRLs develop in approximately eighty-four percent of affected eyes [12]. The factors determining the development of a PRL at a precise location relative to the scotoma are still not well known. Previous studies reported that the PRL was located more frequently to the left of the scotoma (34% to 63% of the cases) [12, 13]. Other studies showed that different PRLs can be used predictably according to various parameters, such as target size or background illumination [14-16]. In subjects with macular disorders, two factors strongly affect reading ability, namely global viewing of words related to the reading visual span, and character discrimination related to spatial resolution [17-19]. Global viewing of words refers to the ability to perceive the word in its entirety, to estimate its number of letters and to perform saccades to completely uncover it. Character discrimination refers to the ability to correctly read individual letters. Spontaneously selected PRLs do not consistently meet both
requirements. In our previous investigations we found that multiple PRLs with complementary functional advantages could be used in a coordinated reading strategy [5, 6, 20] and we emphasized that the two essential capacities for reading, could be allocated to different PRLs used in a combined fashion [5].

Whether and how individuals with central visual field loss could be trained in eccentric fixation is an important issue for the management of people suffering from age-related macular degeneration. A limited number of training procedures using the Scanning Laser Ophthalmoscope (SLO) to readapt fixation behaviour during reading have been reported so far. Nilsson, Frennesson and Nilsson [21] investigated the influence of the SLO training structured in sessions scheduled to be one hour a week over two to seven weeks. In this study, subjects with age-related macular degeneration were trained to use a proposed TRL located above or below the lesion and to renounce to their spontaneously developed PRL. To our knowledge, the feasibility of a training process aiming at developing multiple PRLs has not yet been demonstrated.

Therefore the purpose of this investigation was to evaluate, in subjects with age-related macular degeneration, the use of the SLO to train eye movement strategies for reading, based on a combined use of two preferred retinal loci and to assess the immediate benefits and gain retention. The rationale for our selection of SLO training procedures was based on the observation that the use of more than one PRL in a structured reading strategy can meet the requirements for both global viewing and detailed discrimination [5-7, 20]. All subjects included in the present study reported an altered perception of words, despite conventional reading rehabilitation. Their main complaint was that they missed parts of words, thus expressing their lack of adapted global viewing abilities. We therefore trained them to use in combination with their spontaneously developed PRL, an additional retinal locus, the trained
retinal locus or TRL, fulfilling the needs for global viewing, thus allowing the perception of the entire word. Moreover, considering that intensive training over short periods of time is beneficial in neuro-rehabilitation [22-26], and that reorganisation of the oculomotor system for eccentric reading can be achieved using an intensive training over a two-weeks period in experimental conditions [27], we designed our training protocol to be intensive over a short term.

METHODS

The training study was conducted in three phases. We first carried out a baseline assessment of visual function and reading ability on isolated words in each subject, after which we conducted the intensive SLO training procedure over ten sessions. Each training session lasted an hour. Finally, we evaluated reading performance and reading strategies both immediately after the completion of the SLO training process and three months later.

Subjects

Criteria used for inclusion in the study were the following: (1) presence of a bilateral AMD condition stable over the last year (table 1); (2) visual acuity ranging between 1.5 logMAR and 0.9 logMAR in the best eye; and (3) complaints of reading disturbances consisting essentially of gross difficulty to decipher long words.

Six subjects were initially enrolled in the study (MT, SL, LG, AA, GM, ML). Subject ML, however, was subsequently discarded, as he appeared to suffer from dementia (described in more details in the results section). Ages ranged from 76 to 81 years (mean: 78.8 years ± 1.92
In each subject a stable bilateral macular condition had been present in average for 2.3 years. Contrast sensitivity of subjects’ best eye, as measured with the Pelli-Robson contrast sensitivity chart (Clement Clarke Intl, Haag-Streit, UK) was lower than the one measured in subjects without macular disorder of similar age [28]. These clinical features are shown in table 1. A regular low-vision rehabilitation procedure, including scanning and reading exercises similar to those described by Beaunoir et al. (2000) [29], had been conducted by a low vision specialist, for four to ten training sessions, extending over a period of more than three months. Despite rehabilitation, subjects presented reading difficulties during the SLO evaluation as, for example, reading only the first five letters of a ten letter-word, or guessed, often incorrectly, the end of presented words. In general they were unable to uncover the end of words (table 2). Stability of the clinical condition and previous rehabilitation training allowed the use of each subject as his own control, as no spontaneous recovery was expected. All subjects gave their written informed consent for the procedure and testing methods, all of which were in accordance with the Declaration of Helsinki and had been accepted by the local ethical committee for human experimentation.

**General procedure**

Subjects’ evaluation included visual acuity measurement, scotoma delineation, identification of spontaneously developed PRLs and characterisation of oculomotor strategies during reading. Visual acuity was first determined for both eyes with ETDRS charts (Precision Vision Ltd, USA) (table 1). Based on these values, the remaining evaluation and the training procedure were conducted in the eye with the best visual acuity. For the SLO experiments, subjects were comfortably seated forehead rested at 46 cm in front of the SLO screen, which provides image of 32 x 22 degrees of visual angle [7]. Stimuli were presented on the SLO
screen at a luminance of 30 000 trolands (obtained using the conversion factor reported in Nygaard & Schuchard (2001) [31]). Experiments were conducted in a darkened room.

**Phase I: Initial evaluation**

The scotoma was delineated using the microperimetry software of the scanning laser ophthalmoscope (SLO, Scotometry 3.0, Rodenstock, Germany). The testing method was based on the one described by Sunness *et al.* (1995) [32]. Briefly, the patient was instructed to fixate a cross. The investigator firstly chose a retinal landmark on the SLO real-time image that served as a reference point. Subsequently stimulus points were presented for 500 msec on sites of interest. The order of presentation was randomised. The patient had to press a button each time he saw a stimulus and the response was recorded on the computer. At the completion of the testing a final fundus image was grabbed, where the investigator specified the position of the landmark. The data points were displayed on this image with different symbols for seen and unseen stimuli. Subsequently we presented through the SLO to each subject a series of 32 words varying in length to enable the subjects to become familiar with the testing procedure.

Baseline parameters for the training procedure were determined for the threshold character size for single letters and isolated words and for the oculomotor strategies used to read isolated words. Threshold character size for single letters and isolated words was assessed using three different lists of 32 items of 8 different character sizes (1.5 to 0.8 logMAR) that we projected in a random order onto the retina using the SLO. Threshold character size was defined as the smallest size at which a correct verbal report of the isolated letter or word could be made at the first attempt. The results obtained for the three different lists were averaged. Isolated words were of three types: 3 and 4-letter words, 6 and 7-letter words and 9 and 10-letter words (table 3). Words were matched for frequencies (> 1/1000) and grammatical
category between word-length using the Brulex database [33]. Matching words according to these two parameters made impossible to use words of a single length in a group. Presenting words of different lengths in a random order was intended to restrict subjects’ prediction of the word based on its number of letters. Each word was presented only once to each subject during the whole experiment.

Analyses of reading strategies were conducted according to the method we previously described [5]. To summarize, the SLO was used in conjunction with a program developed in our laboratory for projecting letters, words or paragraphed texts directly onto the ocular fundus. Images of the ocular fundus and the superimposed words obtained during the reading tasks were recorded onto a digital videotape, at a frequency of 25 frames/second. Another program developed in our laboratory allowed extracting eye movements automatically by comparing the frame-by-frame shift of the image position [34]. Scotoma borders and some major retinal landmarks, such as the optic disc and blood vessels were outlined from the microperimetry results to produce a schematic image. Finally, the program reconstructed a “cartoon” of the sequence of the eye movements during reading (figures 3, 4). From these cartoons, we analysed the eye movements’ pattern and identified the PRLs employed during reading. We defined a PRL as an area repeatedly and consistently used during reading isolated words. This area was used by the patient to perform saccades and fixations while deciphering the presented word.

**Phase II: Training procedure**

The results of the initial evaluation phase showed that four (MT, SL, LG, AA) out of five subjects had spontaneously developed an initial PRL that fulfilled the detailed discrimination capacity but prevented global viewing (see details in the results’ section). We designed a
procedure that intended to train the use of an additional area, the examiner’s selected trained retinal locus (TRL), where the presented word could be perceived in its entirety. This area was situated either above or below the lesion on the SLO image. The fifth patient had not developed a PRL despite previous rehabilitation. We trained him to use a TRL suitable for both global viewing of words and detailed discrimination.

Among potentially valuable retinal locations, the area closest to the initial PRL was selected. Visual acuity was evaluated at the initial PRL and at the examiner’s selected TRL (figure 1). This involved the presentation of a tumbling “E” in one of four orientations with the SLO using the visumetry program 3.0. Stimuli were presented in 0.1 logMAR steps. With this technique, visual acuity was defined as the smallest stimulus size at which a correct answer was obtained for three out of four presented stimuli.

We trained three subjects (MT, SL, LG) (figure 1) to use an examiner’s selected TRL above the scotoma on the SLO image (i.e. below the scotoma in the visual field). In one subject (AA) the examiner’s selected TRL was situated on the same side of the scotoma as the initial PRL, i.e. above the lesion on the SLO image, but farther from the scotoma’s border. The remaining fifth subject (GM) was found to use an ill-defined area with preserved global viewing but non-optimal spatial resolution. Based on the results of visumetry, he was trained to use an area below the scotoma on the SLO picture, which presented a better acuity than the initial PRL while still preserving a global viewing capacity (figure 1).

The training process involved the projection of single letters and isolated words onto the retina using the SLO. To facilitate the control of eye position at the beginning of the procedure, fixation was anchored using a cross while words were projected onto the
examiner’s selected TRL (figure 2). Subjects were instructed to fixate the words by alternating between the initial PRL and the examiner’s selected TRL. Subject were trained to use the initial PRL for fine spatial discrimination and the examiner’s selected TRL for global viewing, i.e. to estimate word length and to reach the end of the word. The anchored cross was eventually removed and the subject was asked to repeatedly attempt to scrutinize the word alternating by himself between these fixation locations. When the subject could not voluntarily shift fixation onto the examiner’s selected TRL, the training procedure was repeated from the previous stage using the fixation cross. Verbal feedback by the examiner assisted in learning the use of the TRL. Subject GM, the only subject who had not previously developed a well-defined PRL, was instructed to use only the examiner’s selected TRL.

In each training session the subject was asked to read a 32 single letters and isolated words’ list, displaying a word length distribution similar to that used in the pre-training evaluation, but including only four different character sizes. Character sizes were selected according to the threshold determined during the baseline testing, starting with two initially readable and two initially unreadable character sizes. Once the subject could read all words, the set of sizes was readjusted by removing the largest character size and including a smaller one. Our training process involved presenting the fixation cross and the associated word randomly at two different positions on the SLO screen to avoid subject’s anticipation of the spatial location of the stimulus. Ten training sessions of one hour each were conducted at the same time of the day, with three to four sessions a week. We conducted the sessions at the same time each day to avoid variations of performances due to the circadian cycle. At the end of the SLO training, subjects were encouraged to apply the trained strategy at home. For this purpose, they were advised to use the reading devices, which had been prescribed by the low vision specialist during their previous rehabilitation training.
Phase III: Post-training evaluations

To assess the possible functional changes, an evaluation was conducted both immediately after SLO training and three months later, and findings were compared to those collected before starting the training procedure. Assessment included ETDRS visual acuity and threshold character size for single letters and isolated words, as well as analysis of the eye movements and reading strategies. We finally asked the subjects to give their subjective impressions on the possible improvement due to the training procedure.

RESULTS

Five subjects completed the whole training procedure. The sixth subject, ML, was excluded from the study because he showed severe signs of memory impairment three months following the training. His statement that he did not remember to have been trained in our laboratory emphatically demonstrated his memory loss.

Reading strategies for isolated words

Initial evaluation

Previous to SLO training, four subjects (MT, SL, LG, AA) used a well-defined PRL to read isolated words (figure 1 and table 2). The PRL showed better visual acuity than the examiner’s selected TRL, but was not optimally located for global viewing, preventing these four subjects from reading (figure 3A, 4A). Three of them (MT, SL, LG) had an initial PRL to the left of the scotoma and consequently ignored the end of the words (figure 3A and 4A).
One of these three subjects (MT) showed an additional small scotoma in the vicinity of the left border of the central scotoma on the SLO picture, that repeatedly superimposed on parts of the scrutinized characters (figure 1, 4). The two other subjects (SL, LG) were additionally unable to perform search movements to detect single letters and isolated words initially projected within the scotoma, and to relocate the projected image onto a healthy peripheral area. The fourth subject (AA) had an initial PRL located above the scotoma on the SLO image, but too close to the scotoma’s border, the upper part of the letters scrutinized being often projected into the scotoma. Consequently he often missed the centre of presented words. The remaining fifth subject (GM) used an ill-defined area above the scotoma on the SLO picture. In addition, he presented a highly instable fixation.

Post-training evaluations

Immediately after SLO training, analyses of reading strategies for single letters and isolated words revealed that subjects used the examiner’s selected TRL, as well as additional newly self-selected PRLs (figure 3B). Four subjects (SL, LG, AA, GM) consistently used the examiner’s selected TRL. Three of them (SL, LG, AA) (table 2) used the examiner’s selected TRL most often in combination with their initial PRL. However, under specific conditions (namely single letter deciphering and 1.5 logMAR word reading), one subject (SL) persisted to use exclusively the initial PRL. One subject (AA) used additional newly self-selected PRLs in combination with the initial PRL and the examiner’s selected TRL for reading isolated words. Another subject (GM) used the examiner’s selected TRL alone.

Three months following SLO training, four subjects (SL, LG, AA, GM) consistently used the examiner’s selected TRL either in isolation (GM), or in combination with the initial PRL (LG, AA, SL) (table 2, figures 3C, 4C). The use of newly developed self-selected PRLs was observed in three subjects (SL, AA, GM).
The remaining subject (MT) showed an improved ability to scan the word, only using the initial PRL (figure 4B). This ability was apparently lost three months following SLO training (figure 4C).

**ETDRS visual acuity**

ETDRS values are reported in table 3 and figure 5. Visual acuity evolution across the three evaluation periods was analysed using a one-way repeated measure ANOVA. This analysis yielded a significant difference (F(2,3)= 17.85; p= 0.022). Values measured before and three months following the SLO training significantly improved compared to those measured before the training process (Bonferroni pairwise comparison p=0.012), while the difference was marginally significant between acuities measured before and immediately after SLO training (Bonferroni pairwise comparison p=0.085).

**Threshold character size for single letters and isolated words**

Threshold character size for single letters and isolated words are shown in table 3 and figure 6. A three-way repeated measure ANOVA with subjects (MT, SL, LG, AA, GM), stimulus types (single letters, 3 and 4 letter-words, 6 and 7 letter-words and 9 and 10 letter-words) and evaluation periods (before, at the end of training and three months later) was conducted to explore the impact of the training procedure as measured by the threshold character size.

There was a highly significant main effect of the evaluation periods (F(2, 19)= 46.04; p<0.0005). The post-hoc analysis using Bonferoni correction showed that all subjects benefited from the training procedure both, immediately after SLO training (mean ± standard error: before= 1.255 ± 0.017, immediately after SLO training = 1.055 ± 0.016; p<0.0005) and
three months later (1.084 ± 0.014; p<0.0005). There was, however, no significant evolution after completion of the training procedure (p=0.563).

There was also a main effect of stimulus type confirming that threshold character size varied as a function of word length (F(3, 20)=73.921; p<0.0005). Threshold character size for single letters (0.9 ± 0.019) was lower than for any other word lengths and threshold for 3 and 4 letter-words (1.13± 0.019) was lower than those for 6 and 7 (1.23± 0.019) and 9 and 10 letter-words (1.26± 0.019; Newman-Keuls: p<0.05). Additionally, the retention of the training gains varied with stimulus types (interaction evaluation periods and stimulus type: F(6, 38)= 3.135; p=0.014). To further investigate the retention of the training gains on the different stimulus types we conducted a post-hoc analysis using Bonferroni adjustment for multiple comparisons with α =0.00125. Subjects read significantly smaller character sizes immediately after the end of the SLO training procedure at all word lengths but 3/4 letter-words, despite the fact that a slight improvement was noticeable for the latter (1 letter: before = 1.02 ± 0.029, immediately after SLO training = 0.82 ± 0.022; p=0.006; 6 and 7-letter words: before = 1.41 ± 0.062, immediately after SLO training = 1.15 ± 0.027; p=0.008; 9 and 10-letter words: before = 1.38 ± 0.057, immediately after SLO training = 1.13 ± 0.045; p=0.006; 3 and 4-letter words: before = 1.21 ± 0.062, immediately after SLO training= 1.10 ± 0.045; p=0.513). Three months following the training procedure, gains were retained for single letters and 6 and 7-letter words, as shown by the non-significant difference between results obtained at the end of training and three months later (1 letter: three months later = 0.86 ± 0.016; p=1.0; 6 and 7 letter-words: three months later = 1.13 ± 0.056; p=1.0). In contrast, performances were not retained for 9 and 10-letter words (three months later = 1.28 ± 0.057; p=0.02) and returned to the initial score (p=0.32). For 3 and 4-letter words the statistical test did not reveal any additional change over the whole procedure either (immediately after SLO training - three months later: p= 1.0; before - three months later: p=0.456).
Another main result was that subjects benefited differently from the training procedure, as shown by the interaction between evaluation periods and subjects (F(8, 38)=5.371; p<0.0005). Immediately after the SLO training procedure, all subjects had improved their performances regardless of the type of stimulus. Three months later subjects SL, LG and AA totally retained and even slightly improved, training gains. Subject GM did not fully preserved the improvements, even if his performances were far better than before the SLO training. Subject MT did not retain training gains at all (figure 6). Despite the fact that the interaction subjects, stimulus type and evaluation periods was not significant (F(24; 38)=0.1014; p=0.497), it is interesting to describe individual behaviour. When looking at individual data (figure 6), it appears that all subjects had better performances three months following the training procedure than before for 3 and 4-letter words. For 6 and 7-letter words, three subjects (SL, LG, AA) progressed in deciphering capacities, one subject (GM) retained training benefits, and the remaining subject (MT) partially lost training gains. For the 9 and 10-letter words, one subject (SL) improved, three subjects (LG, AA, GM) partially lost the gains, and the remaining subject (MT) lost all benefits of the SLO training (see arrows in figure 6).

Finally there was a main effect of subjects, as expected regarding the individual variations of threshold character sizes (F(4, 20)=16.443; p<0.0005). The interaction subject and stimulus type was not significant (F(12; 20)=1.100; p=0.087).

Patients’ comments on the modification of their visual perception before and after the training

We asked the patients to give a subjective evaluation of the influence of the SLO training on their everyday life. All patients reported less visual fatigue and improved awareness of the
location of the scotoma. MT reported that two weeks after the completion of the SLO training, she had the impression of an improvement in reading. SL noticed that SLO training enabled a more efficient reading of the panels in the street as well as bus numbers. LG could not report specific subjective improvements but said that, in general, she better coped with her visual field defect. AA applied the taught strategy to other visual tasks. She said she recovered the ability to hand-knit. After the SLO training process, GM started to use a closed circuit television (CCTV) and was able to read with it. He stated that the SLO training allowed him to locate his scotoma in his visual field and, as a result, several visual tasks were easier to accomplish.

**DISCUSSION**

Our observations in subjects with a stable central scotoma and persistent major reading difficulties despite previous rehabilitation, showed that SLO training aiming at combining the use of multiple PRLs improved reading ability. The value of SLO training in subjects with macular conditions had been emphasized previously [21]. This technique allows local visual acuity measurements, estimation of potential global viewing capacity in different areas of the retina and direct understanding of the nature of reading problems. It also enables the guidance of subject’s fixation onto the presented words and a continuous interaction with the subject during the training session. Our schedule of the SLO training procedures was based on recently suggested principles for neural rehabilitation [reviewed in 25] and applied, for example, in individuals with chronic aphasia [24].

**Immediate functional benefits and gains retention**
Our analyses of reading strategies demonstrated essentially that with SLO training, subjects with limited global viewing acquired the capacity to perform eye movements, which allows the perception of the presented words in their whole. The newly adapted oculomotor behaviour included the use of the examiner’s selected TRL, either in isolation or in combination with the initial spontaneously developed PRL and the associated use of newly self-selected PRLs. Four subjects used the examiner’s selected TRL in combination with other areas, whereas the remaining subject used only the examiner’s selected TRL. Interestingly, the development of the newly self-selected PRLs and new oculomotor patterns suggested that the structured training procedure, aiming primarily to develop an examiner’s selected TRL, in fact initiated a more global functional adaptation process. As already suggested in neuro-rehabilitation studies, training might trigger general changes in adaptation strategies and thus may “prime” the brain for future learning [26].

The adaptation of reading strategies were associated with improvements measured in different reading tasks. ETDRS acuity and threshold character size for single letter measurements evolved, as expected, similarly throughout the training. Increased visual acuity was likely related to an increased ability to detect and then relocate stimuli that fell into scotoma’s area. One might also consider whether gains in ETDRS acuity and threshold character size for single letters and isolated words observed following SLO training were non-specific results of the training process, and unrelated to the use of the SLO. This option however, is unlikely. Indeed, all subjects had previously undergone a conventional low vision training procedure, which proved to be unsuccessful in allowing isolated words to be deciphered. In contrast, they became able to do so following SLO training. Moreover, selected TRL was eventually used following training in four out of five subjects.
Assessment conducted three months following the completion of the SLO training showed that gains acquired with this training persisted and that improvements remained for reading single letters but were not retained for 9 and 10-letter words. Deciphering 9 and 10-letter words requires both accurate fixation and adapted saccadic movements, probably more so than those required for isolated letters and short words, which necessitate essentially accurate eccentric fixation. Differences between various reading tasks in terms of gain retention presumably reflected the variation in complexity of mechanisms involved in specific adaptation processes. Indeed, it is conceivable that complex tasks more demanding in terms of plasticity may be more difficult to retain and/or need more extensive training. A similar variability in the retention of performances as a function of the complexity of the task was observed in 400 patients who had followed short-term, intensive procedures for rehabilitation on motor tasks [35].

**Eye movements’ adaptation**

Adaptation of the oculomotor system studied here involved at least two different mechanisms: the first one to achieve eccentric fixation, and the second to reorganise the control of saccades around the coordinates of the initial PRL and the examiner’s selected TRL. The distinction between these mechanisms and their respective complexity has been demonstrated experimentally. Heinen and Skavenski (1992) [36] found in adult monkeys that one day after bilateral foveal lesions, fixation was performed with a new retinal locus, although saccades at this stage of adaptation still maladaptively brought visual targets onto the lesioned fovea. Subsequently, over a period of several weeks, saccades trajectories progressively changed and targets projected directly onto the intact retina [36]. In our study, individual practice of oculomotor strategies during the period following the SLO training might also have influenced the degree of retention of reading ability. Particularly, in one subject (MT) who
could not pursue any reading practice at home, the gains observed immediately after SLO training were eventually reduced, and even return to baseline performances. We therefore suppose that to retain improvements on complex tasks “brush up” periods of training might be advised following structured procedure.

It might be interesting to investigate to what extent the improvements obtained following training for isolated words might reflect subjects’ increased ability to read paragraphed texts. We previously reported in subjects with macular scotoma, a strong correlation between the threshold character size for reading words longer than five letters and for reading paragraphed text [37]. Consequently, following reading training, improvements on longer words are likely to be associated with an improvement on paragraphed text, although the latter requires a more complex adaptation of eye movements - to perform accurate return sweeps, for example.

In subjects with macular disorders, we previously suggested that learning to control eye movements improved the use of the PRL and facilitates the development of additional PRLs [20]. Here we showed that training subjects to combine the use of multiple PRLs in reading tasks also favoured the development of additional individual reading strategies that involves the examiner’s selected TRLs and newly self-selected PRLs to bypass their lack of global viewing capacity.

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REFERENCES


FIGURE LEGENDS

Table 1: Subject’s clinical characteristics

Visual acuity was measured with ETDRS charts. Selected eye: eye with the better visual acuity selected for training.

Table 2: Retinal areas used for reading and the occurrence of eye movements to completely uncover presented words

PRL: initial PRL; TRL: examiner’s selected TRL; nPRL: additional newly self-selected PRLs; Following the training four subjects (SL, LG, AA, GM) used either the examiner’s selected TRL and/or newly self-selected PRLs. Note that, before training, only two subjects were able to perform eye movements to entirely uncover presented words, either sequentially using the initial PRL, or at once using the examiner’s selected TRL. Immediately following training, all subjects were able to achieve the task. In four out of five subjects this capacity was retained three months following SLO training. Note also that the subject that did not retain the ability to uncover presented words also did not retain any functional training gains.

Table 3: ETDRS acuity and threshold character sizes for single letters and isolated words

1: 1 letter; 3 and 4: words of 3 and 4 letters; 6 and 7: words of 6 and 7 letters; 9 and 10: words of 9 and 10 letters. The mean value obtained for each patient and for each stimulus type is reported.
**Figure 1: Scotoma topography**

Scotoma borders were plotted using scotometry, with the brightest (Goldman III) stimulus. In subjects MT, SL and GM, parts of scotoma borders could not be delineated, as the scotoma was not always entirely visible within the SLO analysis area. Locations of the initial preferred retinal locus (PRL) and the examiner’s selected trained retinal locus (TRL) are indicated, as well as the visual acuity measured with visumetry at these locations.

**Figure 2: Procedure for SLO training**

First, fixation was anchored using a cross at the initial preferred retinal locus (PRL) and words were projected onto the location of the examiner’s selected trained retinal locus (TRL). Projected words and crosses varied were randomly presented at two different locations on the SLO screen to induce changes in eye position. The anchored cross was eventually removed and the subject was asked to repeatedly attempt to scrutinize the word alternating by himself between fixation locations.

**Figure 3: The development of the combined use of initial PRL, examiner’s selected TRL, and two new self-selected PRLs for reading isolated words**

The figure shows, as seen on SLO images, three uninterrupted sequences of eye movements performed while attempting to decipher an isolated word presented in 1.3 logMAR. Recordings were obtained in subject LG (A) before SLO training, (B) immediately after SLO training and (C) three months later. In each reading sequence images are numbered in chronological order. Previous to SLO training, the inability to perform eye movements to reach the end of the word “conscience” prevented reading. The subject therefore only read “con”. Immediately following SLO training and three months later, LG adapted his reading strategies and was able to read entirely the words “révolte” and “compagnie”. The arrows
indicate the position of the retinal areas being presumably employed: initial PRL (↓), examiner’s selected TRL (↑), newly self-selected PRLs (↓). The examiner’s selected TRL was consistently used combined with the initial PRL and/or with newly self-selected PRLs. Please note that, on the SLO image, an upside down inversion of the image allows the word and the presented reading strategies to be viewed normally.

**Figure 4: The development, with SLO training, of a progressive uncovering strategy for reading isolated words**

The figure shows three uninterrupted sequences of eye movements while reading an isolated word presented in 1.5 logMAR as seen on SLO images. Recordings were obtained in subject MT (A) before SLO training, (B) immediately after SLO training and (C) three months later. In each reading sequence images are numbered in chronological order. Before training, the subject was unable to read entirely the word “maison”. He read only “mais”. Immediately following SLO training, he became able to read entirely the word “horloge”, performing successive eye movements uncovering segment by segment the entire word with the same retinal area (→→). Three months following completion of the training process, however, the subject could not anymore read entirely the word “liaison”. The vertical arrow indicates the retinal area presumably being employed, here exclusively the initial PRL (↓). MT was, in the study, the only subject of the experiment to lose both SLO training gains, and modification of the eye movement pattern. Note that, on the SLO image, an upside down inversion of positions allows the word and the presented reading strategies to be viewed normally.

**Figure 5: Evolution of ETDRS visual acuity**

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Measures are reported for each subject. *before:* before SLO training; *after:* immediately after SLO training; *three months later:* three months following SLO training. Changes in ETDRS values could be considered significant when greater than 0.1 logMAR [39]. Note that ETDRS visual acuity consistently increased with the SLO training and, globally, gains were retained three months later.

**Figure 6: Evolution of threshold character size for single letters and isolated words**

Threshold character sizes values, in logMAR, are provided for each subject. *before:* before SLO training; *after:* immediately after SLO training; *three months later:* three months following SLO training. Isolated letters and word length categories are considered independently. With subject GM, threshold character size for 6 and 7 and 9 and 10 letter words could not be determined before training, because he was unable to decipher the largest presented stimuli (1.5 logMAR). Therefore, in the graph, he was assigned the minimum 1.6 logMAR level. Note the invariance of the results for isolated letters, contrasting with the variability of the changes obtained for isolated words. Loss of training gains mainly occurred when deciphering longer words. In this regard, measures in subject LG are particularly illustrative, showing continuing improvement in reading single letters and 3/4-letter words, stabilised performance for 6 and 7-letters words, results which contrast with the gain loss observed for 9 and 10-letter words.
Figure 5

Character size (logMAR)

- MT
- SL
- LG
- AA
- GM

before  after  three months later
Figure 6

Character size (logMAR)

single letters

3 and 4-letter words

6 and 7-letter words

9 and 10-letter words

MT
SL
LG
AA
GM
Additional files provided with this submission:

Additional file 3: tableau 3.doc: 30Kb
http://www.biomedcentral.com/imedia/5725097581118826/sup3.DOC

Additional file 2: table2horiz.doc: 26Kb
http://www.biomedcentral.com/imedia/1682260320111882/sup2.DOC

Additional file 1: table 1.doc: 24Kb
http://www.biomedcentral.com/imedia/1691855909111882/sup1.DOC