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REVIEW

Neuro-visual rehabilitation

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Abstract Despite the fact that almost one-third of patients suffer from visual deficits following brain damage; neuro-visual rehabilitation to compensate for visual field deficits is relatively neglected in the clinical setting. This is in contrast to physio and speech therapies, which are the bread and butter of rehabilitative programs. Likewise, programs that address coping with dementia usually concentrate on language, memory and cognitive skills, but often fail to address the deficits experienced by the subset of patients suffering from progressive cortico-visual dysfunction. Herein, we will review the different approaches to neuro-visual rehabilitation, mainly concentrating on restorative and compensatory treatments. While the first claims to restore vision in the blind visual field, the latter attempts to improve the use of the remaining intact field. These approaches differ in their premise regarding the ability of the adult human brain to adapt following damage, reflecting different attitudes toward the presumed treatment target organ. While restorative therapies claim to reactivate inactive neurons within or around the damaged cortices, compensatory approaches aim to improve voluntary eye movements to compensate the visual loss. We will also briefly discuss the use of optical devices for bypassing the visual deficit as well as the use of the blind-sight phenomena to convert non-conscious visual abilities in the blind visual field into awareness. The various therapeutic approaches will be discussed in the context of patients suffering from hemianopsia and in patients suffering from posterior cortical atrophy. We will argue that of all, the compensatory strategies have shown the most promising results.

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Introduction

While neurological rehabilitation is a common procedure following acquired brain damage, it is usually limited to restoring physical strength, mobility and language abilities. Despite the fact that 30 % of patients suffer from visual defects following brain damage and the estimated incidence of visual field defect in the elderly stroke patients (>65 years) is even higher, reaching 40–60 % [1], restoring vision is relatively neglected [2]. This bias toward motor and language skills is usually a result of the assumption that the ability of a patient to ambulate independently and their ability to communicate with others are more meaningful to daily life than improving visual abilities. However, it is interesting to note that the fear of losing eyesight is one of the most significant concerns among the adult population (ranked fourth after immunodeficiency syndrome, cancer and Alzheimer's disease) [3].

Whereas plasticity of the young brain after damage is a broadly accepted concept, the ability of the adult brain to adapt is controversial [4, 5]. This controversy has given rise to two distinct approaches to rehabilitation: methods that rely on the hypothesis that the adult brain can change and, therefore, aim to restore vision in the blind visual field, and methods claiming that the adult human brain is stable and is unable to change, and attempt to improve the use of the remnant seeing visual field.

In the current article, we will review the various methods that are currently available for the treatment of cortical driven visual deficits acquired in adulthood.

In general, four approaches for neuro-visual rehabilitation are currently dominant in the literature:

1. Substitution approach using substitutional optical devices to bypass the visual deficit.
2. Restorative therapies restoring the blind field by improving the sensitivity of the residual neuronal tissue within or bordering the cortical damage.
3. From blindsight to sight therapies transforming unconscious visual abilities in the blind visual field into awareness.
4. Compensatory therapies which do not claim to restore the missing visual field but rather compensate for the deficit with better control of eye movements and better visual processing abilities.

Herein, we will review the literature in relation to hemianopic patients, as well as discussing rehabilitation in patients suffering from the neurodegenerative occipital disease, Posterior Cortical Atrophy (PCA).

Homonymous visual field defect is the most common visual injury following cerebrovascular accident (CVA) caused by damage to the post-chiasmal tracts (typically optic radiation or primary visual cortex) [1, 6, 7]. This damage is often accompanied by additional damage to higher visual areas (extrastriate cortical areas), to the occipital white matter and to the posterior thalamus. Spontaneous recovery of vision can occur up to 3 months following the acute event. However, this spontaneous process is usually partial and occurs in only 20–30 % of patients [8]; spontaneous recovery occurs more in the peripheral visual field [9]. About seventy percent of hemianopic patients exhibit preservation of the central five degrees or less of their visual field (macula or foveal sparing) [6]. Nevertheless, patients complain about ongoing difficulties in their everyday visual functions such as navigation, visual search and reading.

As mentioned above and as will be detailed below, the vast majority of papers dealing with visual rehabilitation focus on a particular deficit, the visual field loss relating to damage to V1 or to the visual pathways synapsing in V1. However, other cortical areas higher in the visual hierarchy may be damaged as well. There are some examples in the literature of successful treatments for higher neuro-visual disorders, e.g., improving stereopsis and convergent fusion [10, 11] and improving visuospatial perception [12].

The substitution approach

The substitution approach advocates an optical alternative to the blind field, mainly using prisms either to tilt the image from the blind into the seeing field (Fig. 1) or to expand the visual field. Several optical solutions have been proposed over the years, but side effects including diplopia and confusion have limited their success [13]. Nevertheless, several groups have reported that hemianopic patients favor substitutional prisms for expanding their visual field up to the point that they were eligible for driving licenses [14], experienced improved mobility by being better able to avoid obstacles [15, 16], and improving their quality of life [16]. In general, this approach was reported to be preferred by patients, even compared to sham prisms [17].

Restorative therapies

According to the *residual vision activation theory*, cerebral visual injury is usually not complete, and several structures within or around the affected area remain intact [18]. Residual populations of neurons may be found in penumbral areas of partial damage at the border of the damaged area or as intact tissue "islands" within the damaged area. These residual functional populations will be functionally reflected as a transition zone within the blind visual field.

According to this approach, the visual field is not binary mapped into blind and intact areas, but rather is composed of three categories: (Fig. 2) (1) areas of complete blindness, in which the subject cannot detect any visual information. These areas are wired to degenerated neurons; (2) areas of normal vision, in which the patient can reliably detect visual stimuli. These areas are processed by intact active neurons; and (3) areas of the visual field in which there is visual stimuli identification, but this identification

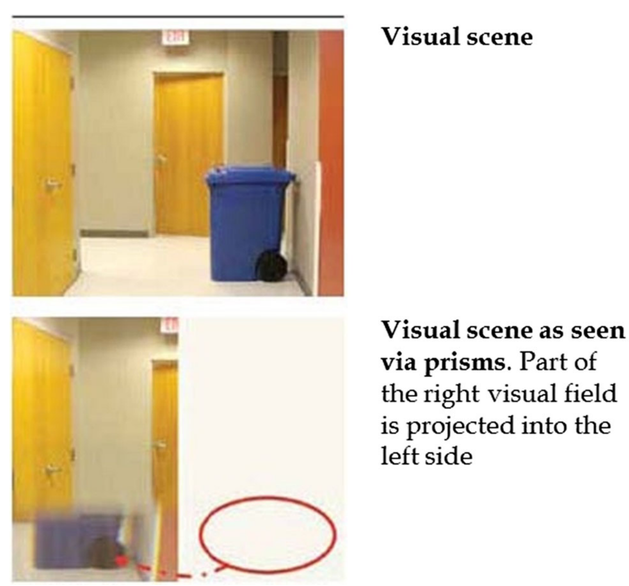


Fig. 1 Substitutional device. Image observed without substitutional optical device (*above*), and through prism lenses that divert the object located in the right field into the left field (*below*)

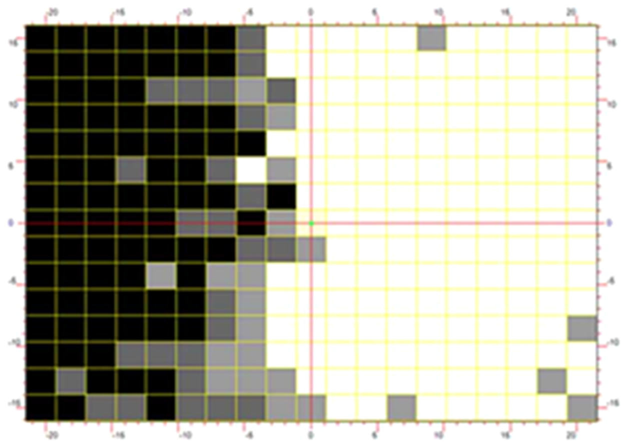


Fig. 2 Visual field obtained via high-resolution perimetry. According to the restorative approach, the visual field is divided into blind damaged areas (*black regions*), intact areas (*white regions*) and transition zone (*gray regions*) which contain intact neurons that are inactive due to disuse

is inconsistent. These portions of the visual field are processed by intact neurons that are not active enough due to disuse. The last visual field category is defined as a residual visual field or transitional zone. Restorative approaches claim that repeated and intense stimulation of the residual zones will alter the partially active neurons into steady and stable active neurons [19, 20].

To design Vision Restoration Training (VRT) for a specific patient, the residual visual fields have to be clearly identified. To that end, high-resolution perimetry is used. In this method, small white dots are projected in 500 different locations on a darkened computer screen and the subject is required to press a button when he identifies a stimulus. Fixation is kept via a central task such as identifying color change in the screen center. Stimulus presentation at each location within the visual field is repeated five times. Blind areas are defined when no stimulus is identified, normal vision areas require full identification and residual areas (which are the target of treatment) are those areas in which identification of the stimulus is inconsistent (i.e., identification of less than 5 stimuli within the region).

Once demarcated, the residual visual areas will be intensively stimulated. The working assumption is that intense stimulation of residual visual zones will arouse and reactivate these partially activated neuronal populations. This reactivation will strengthen synaptic connections and eventually lead to an extended visual field [21]. According to the "minimal residual structure" theory, preservation of even 10–15 % of the neurons enables recovery of the visual functions. In other words, even a paucity of residual neurons in the affected neuronal tissue is sufficient for visual field recovery [22].

The first study to suggest the benefits of the restorative treatment was by Zihl and von Cramon [8] who claimed an improvement in the visual fields of 55 patients with post-chiasmal brain damage following intensive stimulation within the transition zone. Unfortunately, subsequent studies demonstrated that the results were unreliable due to methodological problems, including failure to maintain fixation during the examination of the visual field (post training).

A subsequent study conducted in 1998 demonstrated partial improvement in visual fields following intensive computer training in patients suffering from post-chiasmatic and optic nerve damage [19]. Patients were trained to identify stimuli in the transition zone, practicing daily for 6 months. This report was accompanied by the provocative statement that "those who are blind can now see" [23].

These reports have led to the development of specialized computer software and its marketing through NovaVision [24]. The software includes intensive training for one hour per day, 6 days a week for 6 months. In every session, patients are guided to concentrate at a central fixation point, and respond whenever they see light projected in any other parts of the screen. Each run includes ~1000 stimuli projected to the transitional zone.

Since its establishment, *NovaVision* and the restorative treatment have elicited skepticism and disagreement among clinicians treating patients with neuro-ophthalmological damage [24]. The disputes are mainly related to the ability of the adult brain to restore visual functions [4] and, in particular, the changing ability of neurons' activation patterns as a function of intensive practice. It is important to note that even if we accept that the adult brain is able to restore its lost visual functions, not all patients are expected to benefit from this kind of treatment, since only patients with incomplete damage are suitable for this rehabilitative method [9, 25, 26].

Another criticism is related to the method of assessing efficacy. Debate revolves around the question of whether the improvement reflects real recovery or is a consequence of measurements' artifacts. The ability to control fixation in high-resolution perimetry is problematic and other methods of perimetry that are sensitive to fixation control did not detect enlargement of the visual field following restorative treatment [24, 26].

Treatment-induced visual field enlargement seldom exceeds 5 degrees of the visual angle, although a few cases have reported larger field expansion [27].

Visual field searching requires ~20° of visual field on each side of the fixation point [28] and, thus, expansion of the visual field of only 5° is not expected to harbor any significant functional value. In contrast, reading requires preservation of the central 3°–5°. Thus, theoretically restorative treatment should be effective for improving reading abilities. However, reading improvement following restorative treatment was found to be limited and did not characterize all patients [27]. This was referred to the fact that reading is guided to a large extent by processing parafoveal information which is essential for planning eye movements during reading [29] and, thus, depends on more than foveal vision.

Finally, the cost and the time that need to be invested in this treatment (~90–180 h) do not suit all patients. The restorative treatment is designed to treat the damaged field only, but the visual field deficit is not the only factor that affects patients' function. Hemianopic patients' daily visual function is known to be significantly affected by the patients' ability to adjust their eye movements to the acquired visual deficit; a point which is unaddressed in this kind of treatments.

From blindsight to sight therapies

This line of treatment makes use of the blindsight phenomenon in which hemianopic patients, despite their inability to see in their blind visual field, are able to detect the existence of an object, its location or its movement within their blind field, above a chance level during forced choice tasks [30, 31]. Following damage to early visual areas, visual information along the main pathway (projecting from the eye through the lateral geniculate nucleus and into the primary visual cortex) is damaged. However, visual information continues to flow through the indirect pathway which passes through the superior colliculus into the extrastriate cortex. This indirect pathway is thought to be responsible for the blindsight phenomenon [30].

Though the blindsight phenomenon was described in the early seventies, its use was only recently suggested for rehabilitative purposes. The hypothesis underlying this treatment is that unconscious visual capabilities can be improved following training and, furthermore, with appropriate training, unconscious vision can become conscious.

Training using this approach includes intensive practice to react to stimuli projected inside the blind visual field (rather to the transition zone). The stimuli are projected either near or far from the fixation point and the patient is asked to identify stimulus identity, its position or its direction of motion—all in forced choice decision tasks.

A relatively small number of studies have been published on this method and the reported results are inconsistent [32]. Stoerig reported that with practice, subjects could use this ability in daily life [33]. Chokron et al. reported a clear improvement in performing blind visual field tasks, following forced decision task training. Moreover, improvement was also reported in objective visual field measurements [34].

It is important to note that improvement in forced decision tasks in the blind field could stem from other reasons that are unrelated to increasing awareness of the stimuli (for example, due to patients' increased tendency to report stimuli in the blind field following training, even without a change in awareness of those stimuli, or due to increased awareness to associated cues [35]).

Compensatory therapies

The purpose of these approaches is not to restore the blind field, but to develop effective strategies to compensate for the deficit by learning how to re-adjust eye movements and visual information processing to the new situation.

As demonstrated in numerous studies, impaired visual function in hemianopic patients is explained not only in light of the visual deficit, but also by the pattern of impaired eye movements. Patients find it difficult to scan the visual scene fast enough to percept it as a whole, and they tend to turn their gaze first toward their seeing field and linger there considerably longer than at the damaged field [27, 29, 36, 37].

Despite having normal language abilities, many patients report major difficulties with reading. These difficulties are manifested as slow reading, misreading due to guessing, word loss along the line and difficulty in locating the beginning of the next line. Reading is mostly affected in the blind field direction, such that in English, patients with right field defects have more difficulty than those with left visual defects [27, 29, 38, 39]. Saccades in the direction of the affected field are smaller in amplitudes and many regressive saccades are seen. In addition, fixations are elongated. As a result, visual scanning is not systematic and is very time consuming [6, 27].

Compensatory therapies include systematic training for eye movement emphasizing its use for reading and visual search. Patients are taught to intentionally move their eyes and whilst doing so, their visual field border into their scotoma region. This shift brings the information from the blind visual field into the seeing field for further processing. There is no attempt to change the size of the scotoma (as in the restorative methods) but rather alternate the field of view.

Training eye movements to improve visual search mainly includes tasks in which the patient is required to perform intended and conscious eye movements in the visual space (e.g., detection of the target stimuli in a crowded visual array or following a sequence of stimuli in a chronological order; eye movements are practiced in a narrow and a wide visual field, Fig. 3a). By moving the eyes across the entire visual display, the perceived visual field enlarges. Patients learn to perform efficient saccades into their affected visual field and systematically scan the array to perceive a larger part of the visual stimulation and compensate for the visual field loss (e.g., [39, 40]).

Procedures for training eye movements to improve reading are mainly addressed to teach patients to perceive the entire word prior to reading it. Patients are guided to direct their gaze to the beginning or the end of the word, according to their visual field defect (in English, patients with left visual field deficit are trained to look first at the beginning of the word, and patients with right visual field at the end, Fig. 3b). As training progress, longer words are displayed and presentation duration is reduced, so that patients are required to perform faster and more effective saccades to capture the entire word before it disappears. Patients are taught to perceive the entire word before reading it, to avoid the common strategy of guessing the word based on partial visual information [9, 29, 41, 42].

The Compensatory approach has proven to be efficient in several studies (e.g., [6, 29, 36, 41–43]). Following treatment, improvement in the studied functions of visual search and reading, as well as normalization of eye movements, was demonstrated. The improvement was stable and had functional significance; hence its importance. In addition, the compensatory approach is much cheaper than VRT and requires significantly shorter training time (7–25 h).

As reported by Schuett et al. [44], improvement following compensatory training is specific and cannot be generalized to other visual functions (reading only improves following eye movement training targeted at reading, and visual search only improves following eye movement training targeted at systematic scanning of the visual space). One possible explanation for this specificity is that reading and visual search are specific applications, unique to the visual, attention and oculomotor systems. Visual information processing of reading material requires a different strategy to the one that is required for processing a busy scene (e.g., different saccades amplitudes).

Direct comparisons of restorative and compensatory treatments have demonstrated a clear advantage to the latter [45]. Participants were trained either with visual search tasks using eye movements to look for a specific digit in a visual array (compensatory therapy) or with presenting letters to their blind field borders (restorative therapy). The training sessions were identical in their length and frequency. Better visual scanning and higher frequency of eye movements toward the blind visual field

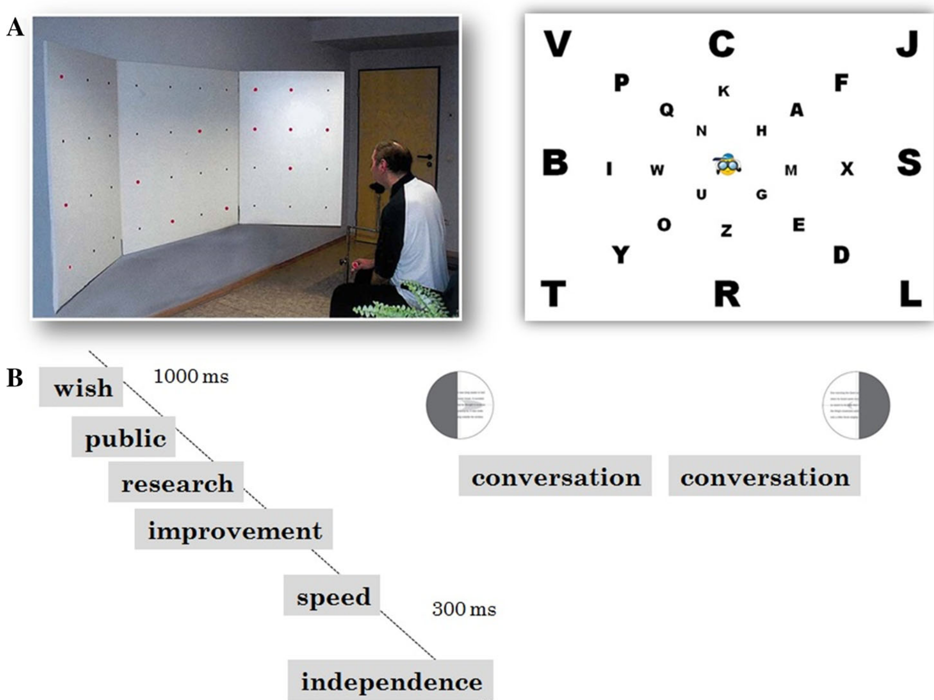


Fig. 3 Compensatory approach training tasks examples. **a** Eye movement tracking tasks, in which patients are asked to perform intended and conscious eye movements to locate the target stimulus (in this example on the left, a *square* composed of four *red dots*) or track stimuli according to a chronological sequence (in this example on the *right*, alphabetical sequence). The stimuli are presented in either small or large visual field. **b** Reading words training. Words are presented for short periods and patients are asked to perceive the entire word before reading it. The *number of letters* in the word increases and presentation time diminishes, through the training progress. In order to perceive the entire word, patients with left hemianopia are required to fixate at the beginning of the word, and patients with right visual deficit, at its end.

were demonstrated in the compensatory therapy group only, while reduction in scotoma size was not reported in either group. Subjective descriptions of improvement in daily visual tasks were observed in the compensatory training group only.

Reading difficulties and visuo-spatial impairments are not limited to steady visual cortex damage, as following trauma or stroke, but also characterize progressive damage as observed in neurodegenerative diseases that affect the visual cortex such as that seen in patients suffering from Posterior Cortical Atrophy (PCA). PCA is a neuro-degenerative disease that specifically affects occipital and parietal cortices and is clinically expressed in selective and progressive functional visual deterioration [46]. PCA patients report many difficulties in their everyday visual life, including eye-hand coordination, navigation, visuo-spatial search, and spatial and gestalt perception [47]. Substantial reading difficulties are reported in 80–95 % of patients [48, 49].

Similar to reports in hemianopic patients, PCA patients also use inadequate eye movements for reading. Patients experience considerable difficulty tracking written text, fixation losses are frequent and occur along the row and between rows and patients find it difficult to go back and find their location along the text [49–51].

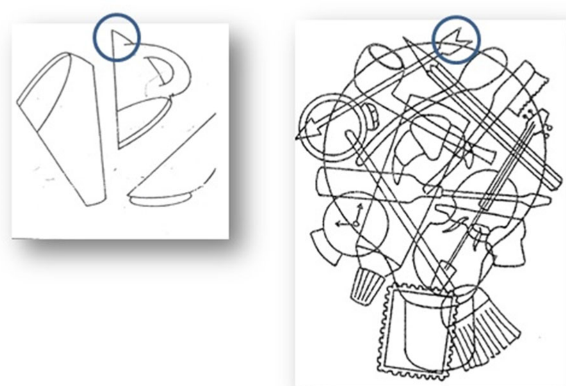
Patients report better experiences with reading single words than reading a text. Furthermore, while reading a text, a spatial bias occurs and greater impairment is experienced during reading of later versus earlier paragraphs and in the center of dense or crowded regions [50]. In addition, PCA patients tend to be better able to read words written in smaller rather than larger font. PCA patients tend to perform smaller and delayed saccades in comparison to controls [52].

The pattern of inadequate eye movements is not unique to reading and can also be observed in visual search tasks. PCA patients tend to focus their gaze at salient visual areas in the array and this tendency is stable and does not vary according to task requirements. This is in contrast to healthy sighted subjects in which eye movements are dynamic and task dependent. As in reading, patients tend to perform shorter and delayed saccades which limit their ability to integrate visual information from different parts of the stimuli [53].

Concentrating on one element in a *visual array* at a time may prevent the patient from perceiving the global picture, a phenomenon known as *simultanagnosia*. This may also result in object mis-identification [54]. For example, one patient in our clinic identified a glass fragment as a beak (focusing on the blunt edge) and hence assumed the object to be a bird (while ignoring the rest of the object components, Fig. 4). *Simultanagnosia* was suggested to be related, at least in part, to impaired eye movements, preventing patients from integrating visual information across the entire visual space [52, 55, 56]. Impaired ability to integrate information across a large visual array may also explain the difficulties patients experience in reading large font letters. The large letter cannot be perceived at a glance and the reader is required to integrate the information from relatively distant areas in their visual space. Failure to integrate the distributed visual information prevents the patient from identifying the letter.

Our clinical experience has taught us that compensatory treatments are also effective for treating PCA patients. We are not familiar with similar experiences in the literature. As with hemianopic patients, we treated patients with PCA using a variety of exercises to improve their awareness of eye movement and teach them to direct eye movements toward a specific visual target in accordance with task requirements (Fig. 3). Patients are trained to perform saccades that are gradually increasing in terms of their amplitude and rate. Other exercises include systematic visual search of the text before reading it and perceiving the entire word (avoiding guessing on the basis of partial visual information) to improve reading abilities.

A different approach to improving reading in PCA patients was reported by Yong et al. In light of the finding that PCA patients performed better when asked to read



Taken from the *Hooper visual organization tests*

Taken from the *15-object test*

Fig. 4 Object mis-identification due to concentrating on the local elements. *Left* patient identified the object (taken from the Hooper visual organization test) as a bird: he identified the glass fragment as a beak and hence assumed the object to be a bird (while ignoring the rest of the object components). *Right* patient hesitated whether the arrow head (taken from the 15-object test, based on Poppelreuter-Ghent's overlapping figures test) is indeed an *arrow* or a cat ear. He did not use his eye movement to track the object along its length, to determine its identity based on the entire available information single words as compared to an entire text, the researchers developed a tool that displays a single word in an isolated window at each time point. This word isolation contributes to minimizing spatial and occulo-motor requirements while reading and was able to improve reading abilities in patients [50].

In conclusion, we reviewed three therapeutic rehabilitation methods to treat neuro-visual defects that stem from cortical damage.

Restorative methods assume that intense training at the transition zone is able to re-activate residual neurons located within or at the borders of the damaged area. Repeated practice strengthens synaptic connections with residual tissue and improves visual function in the blind visual field.

Blindsight-based methods intend to strengthen the indirect pathway in which visual information goes directly to extrastriate areas. Intensive training using forced decision tasks in the blind field may be able to improve the capabilities of the blindsight and to transform unconscious into conscious vision.

Compensatory methods do not attempt to restore the visual loss but rather to compensate it. This is done by training aware and intended eye movements to divert the perceived field into the blind field and, thus, compensate for the scotoma. The target organs for these methods are neither the residual neurons nor the indirect pathways. Compensator approaches aim to strengthen the pathways responsible for eye movements, similar to what we know from rehabilitative physiotherapy where strengthening the limbs is conducted following motor cortex damage.

On the right—the required fixation place as a function of the visual field deficit localization. To perceive the entire word, patients with left hemianopia are required to fixate at the beginning of the word, and patients with right visual deficit, at its end.

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Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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