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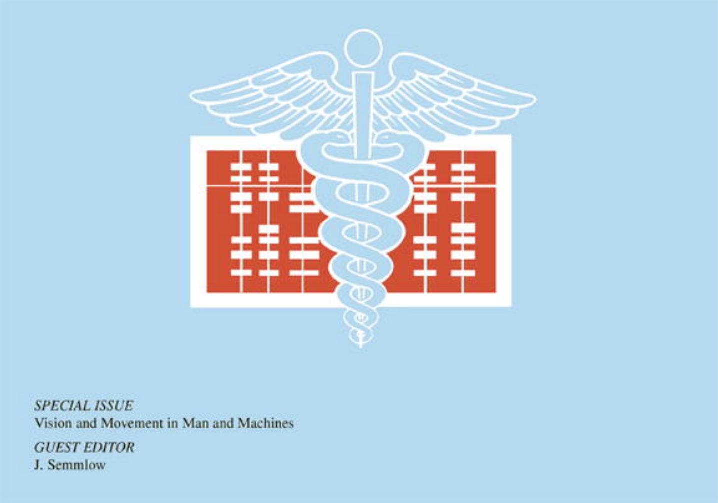

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Foveal versus parafoveal scanpaths of visual imagery in virtual hemianopic subjects

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Abstract

Sophisticated string analysis [compressed regional string analysis, cRSE] shows significant differences following therapeutical masking of the foveal region during a virtual hemianopia. The visual imagery scanpath is done over a compressed mental image that needs longer fixation duration but fewer saccades than the real image. Combination of different viewing tasks with types of pictures permits to show how scanpath top-down strategies can be enforced or decreased by proper combination of task and picture; this is influenced by the mask of fovea versus no-mask of fovea difference, with bottom up mechanisms becoming more important with loss of foveal viewing strategies in the mask condition.

Keywords: Scanpath eye movements; Visual imagery; Virtual hemiblindness; String editing; Markov analysis; Abstract versus realistic pictures

1. Introduction

Several methods to analyse the eye scanpath [1–9] have been tested in the past (see Fig. 1). Besides the standard analysis like calculation of fixation durations, number of saccades in certain regions of the picture and the global-local ratio of scanpath saccades [3], there are statistical, more regionally weighting methods as the *Markov analysis* (MA) [6–9] of zero and first order; and methods of *string editing* (SE) primarily used in linguistics and genetics, that have been introduced by Stark and others: Stark et al. [2,5,7,8], Zangemeister et al. [3,4] since the early nineties into the field of scanpath analysis(see Fig. 2).

We have used and compared regional *SE* (RSE) and compressed RSE (cRSE) where direct repetitions of string-contents are deleted. Further, we have developed a vectorial representation of scanpath strings, Vector SE [VSE], and the weighted VSE [wVSE], where the string vector is weighted according to the frequency of occurrence of similar directions within strings. This latter method has the advantage of working independently of the setting of *a priori* (geometrical) *regions of interest* (ROIs) or *a posteriori* (intelligent, depending on picture content) ROIs (Fig. 3). In the case that ROIs are used, it is obvious that an a priori setting of ROIs favours the analysis of *bottom up* (BU) behavior, and a posteriori setting a *top down* (TD) behavior of the scanpath string.

1.1. Visual field defects

Patients that are blind on one half of their visual field i.e. hemianopic [10–17], usually due to occipital stroke or tumor, show specific oculomotor adaptations due to spontaneous and therapeutic changes that have been reported over the years [14,18,19]. Using specific training regimes, they may be able to adapt and circumvent this half-field blindness, and may also show specific changes in their visual imageries [20–27]. Using a previously [28–31] described computer simulation of such a visual field defect on a visual display terminal (VDT) we posed the question:

Is it possible to enhance and record the effect of this adaptation through "training" of healthy subjects with a virtual hemianopia by enlargement of the 50% horizontal field defect towards the "healthy" seeing side (SHF) by +5°, in analogy to the "forced used therapy" developed by Taub et al. [34] in hemiparetic patients where patients were forced to use only their paretic limb?

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2. Methods

Comparing the different analytical options we decided to use the cRSE for analysis of our recordings in 20 normal subjects experiencing a complete dense 50% virtual homonymous hemianopia–with 10 of them undergoing an additional training of 10 min with enforced virtual hemianopia of 55%, whereas the other 10 underwent a sham training of the same duration. The technique of inducing virtual hemianopia has been described by us before [28–31]. In short, it consists of an IR-reflection eye movement monitor (0.1° resolution; overall bandwidth 0–250 Hz) that has an active link to the 23” screen that is viewed by the subject and where a dark grey blinding of 50% or 55%, respectively, of the viewed image occurs directly related to the eye movements (overall latency of the generation of the mask 8 msec).

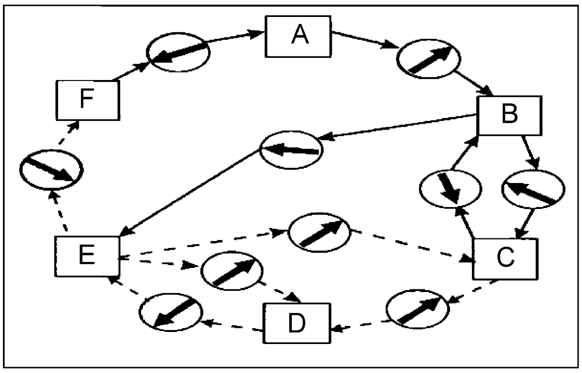


Fig. 1. Scanpath theory: Eye fixations shown as connected sequence resulting in a sequential string of visited regions of interest (ROIs) (lettered squares) and saccadic eye movements (circles with arrows) shown by solid arrows form the “feature ring” of the scanpath theory in the non-iconic model of this example. The variability of ROI-sequences is represented by the dashed arrows.

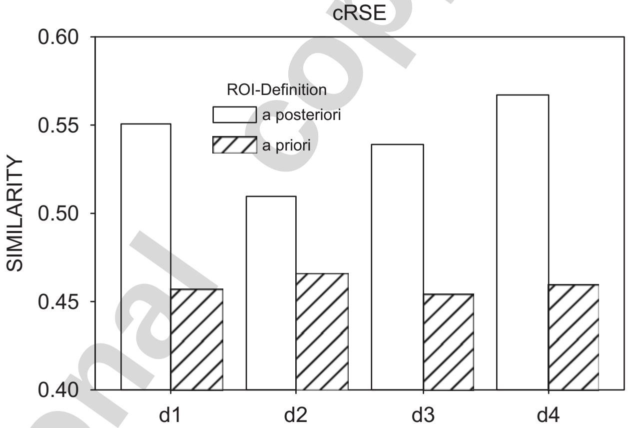
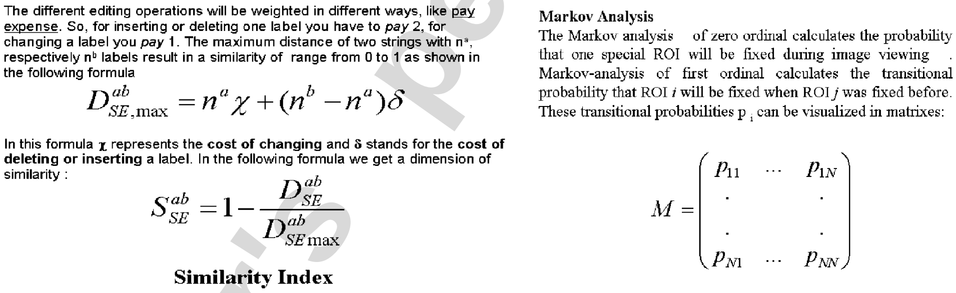


Fig. 4. Similarity as a function of ROI definition and set. Highly significant differences of the ROI definition by regional SE. *A posteriori* differentiates better than *a priori*.



The different editing operations will be weighted in different ways, like pay expense. So, for inserting or deleting one label you have to *pay* 2, for changing a label you *pay* 1. The maximum distance of two strings with n^a, respectively n^b labels result in a similarity of range from 0 to 1 as shown in the following formula

$$D^{ab}_{SE,\max} = n^a \chi + (n^b - n^a)\delta$$

In this formula χ represents the **cost of changing** and δ stands for the **cost of deleting or inserting** a label. In the following formula we get a dimension of similarity :

$$S^{ab}_{SE} = 1 - \frac{D^{ab}_{SE}}{D^{ab}_{SE\max}}$$

Similarity Index

Markov Analysis

The Markov analysis of zero ordinal calculates the probability that one special ROI will be fixed during image viewing . Markov-analysis of first ordinal calculates the transitional probability that ROI *i* will be fixed when ROI *j* was fixed before. These transitional probabilities p_i can be visualized in matrixes:

$$M = \begin{pmatrix} p_{11} & \cdots & p_{1N} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ p_{N1} & \cdots & p_{NN} \end{pmatrix}$$

Fig. 2. String editing (SE) (left) and Markov analysis (MA) (right) algorithms used; SE: definition of similarity index; MA: the Markov analysis of zero ordinal calculates the probability that one special ROI will be fixated during image viewing. MA of first ordinal calculates the transitional probability that ROI *i* will be fixated when ROI *j* was fixated before. These transitional probabilities *p* sub *i* can be visualized in matrices.

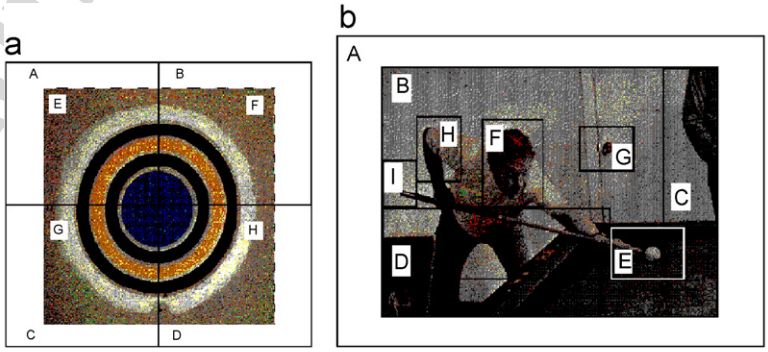


Fig. 3. A priori and a posteriori analysis: (a, left) Geometric *a priori* definition, “Spring Cool” by Ken Noland, 1962; (b, right) Semantic *a posteriori* POI definition, “Deadeye” by Lane Terry, 1971.

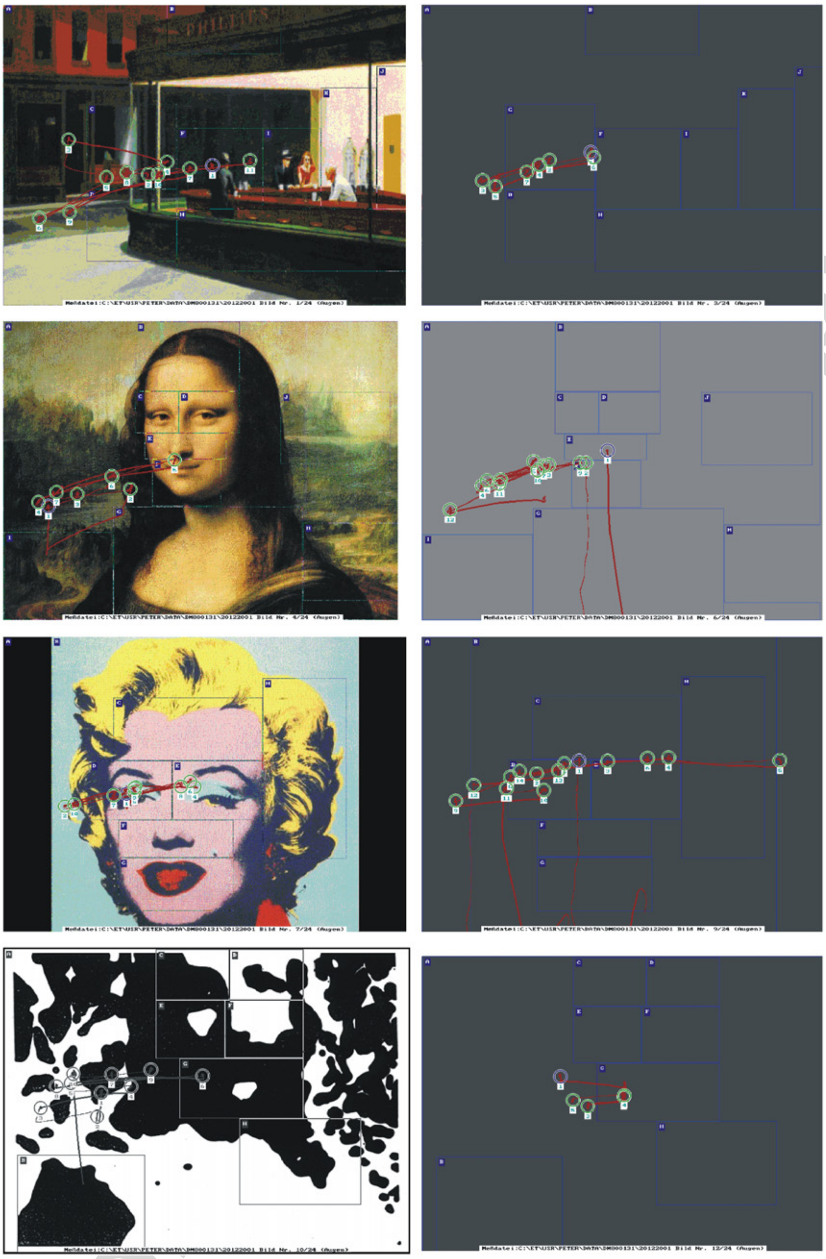


Fig. 5. Scanpaths of pictures 1–4. Left column: real scanpath; right column: imagery, Set2: 2: 50% mask to right.

Compressed RSE was obviously superior to the other methods in showing particular string similarity differences between Set1(d1) and Set4 (d4).

[Set1 = initial recording, Set2 = with mask training or sham training, Set3 = control recording after "training"—all on the same day sequentially done; Set4 = control recording 14 days later, no training]. For statistical comparisons we used the Mann–Whitney U test between all tasks.

Using a posteriori ROIs had the advantage of showing more sophisticated differences between single sets. This is demonstrated differentially in Fig. 4, where the extra-mask training shows up with a significant ($p < 0.001$) similarity decrease at Set2, the time when this training was performed. The *sequence* of pictures that our subjects viewed [5 *sec*, 2 *sec pause*, 5 *sec visual imagery viewing the blank screen*] consisted of three realistic, three abstract, two search pictures (*see Fig.* 5 *showing examples of one half run.*). The *task* how to view these pictures was: first easy, then detailed, and finally recollection viewing [25].

Characteristical examples from Set 2 (d2) are given in Fig. 5.

3. Results

Interestingly, an *a priori cRSE* comparison of string similarities—that favors analytically the BU view—of the MaskGroup with the NO-MaskGroup between Set1 and Set3,

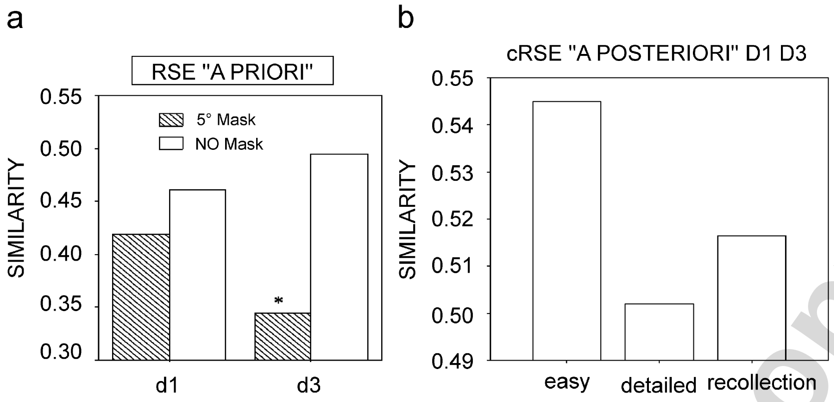


Fig. 6. Compressed RSE as a function of set (a, left) and task (b, right).

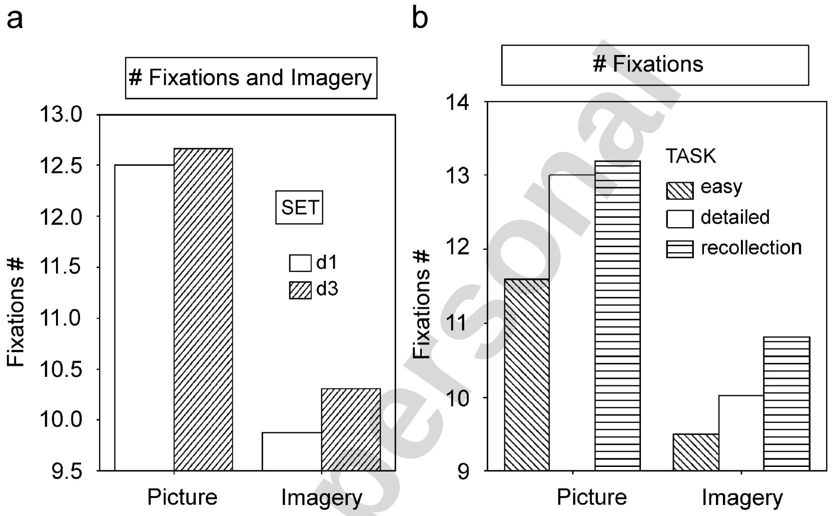


Fig. 7. Number of fixations as a function of [real vs. imagery] and set (a, left), and task (b, right).

shows the mask effect more differentially (Fig. 6a): Mask training is followed by *decreased* similarities, NO-Mask sham training by an *increase* of string similarities. That these significant effects hold true also with the *a priori compressed Markov* analysis, where more regional aspects are weighted was additionally also found. This is a demonstration that the extra 5% mask generated more BU dependence of scanning and searching.

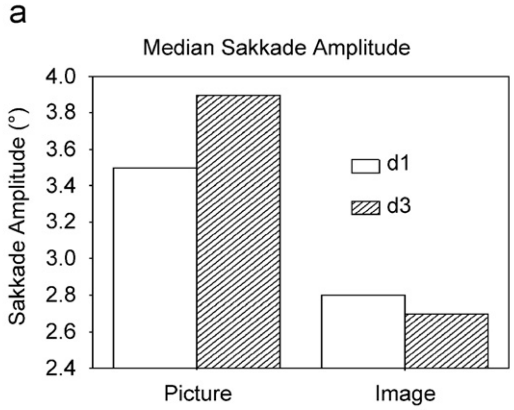
Results of the cRSE comparison between set1 and set3 with a posteriori ROIs (Fig. 6b) showed significant differences ($p < 0.01$) between the above task as a function of the intervening mask—compared to sham-training, whereas the other conditions did not show such similarity differences. Obviously, *detailed* viewing, where foveal fixations are important, was decreased; whereas *easy* viewing showed increased similarities, where para- and extra-foveal viewing is more often contributing to the similarities of scanpaths.

Number of fixations (Fig. 7a) did not differ between picture and image, but between Set1 and Set3—as an indirect sign of the scanpath's decrease of magnitude. However, number of fixations as function of different tasks demonstrated significant differences ($p < 0.01$) between easy compared to detailed or recollection viewing— "easy" showing the lowest number of fixations during set3 (Fig. 7b).

The *mental image* or *visual imagery* showed the tendency to be miniaturized as described previously by Gbadamosi and Zangemeister [22], *Fig.* 8, *statistics(a), and example scanpths(b).* The statistical effect shown in the amplitude distribution as a function of mask training and imagery is shown in Fig. 8a: In general, with visual imagery the amplitudes become significantly smaller. The special effect of the training (set3 versus set1) is that particularly after the training amplitudes decrease for the imagery.

An example of progressive miniaturization of the scanpath with imagery 5, 30, and 60 s after the real picture viewing ([22] is shown in Fig. 8b).

The significantly increased fixation durations in d3 (Fig. 9b) demonstrate the "facilitated mobilisation of information [23,24] at work. This means, that with imagery the time to recall the picture through successive eye movements is significantly longer than the "real" scanpath. It shows also that with training (set3) this process can be facilitated.



b

This figure shows an example of progressive miniaturisation of the hemianopic scanpath with imagery 5sec [upR], 30sec [downL], 60sec [downR] after the real picture viewing [upL].

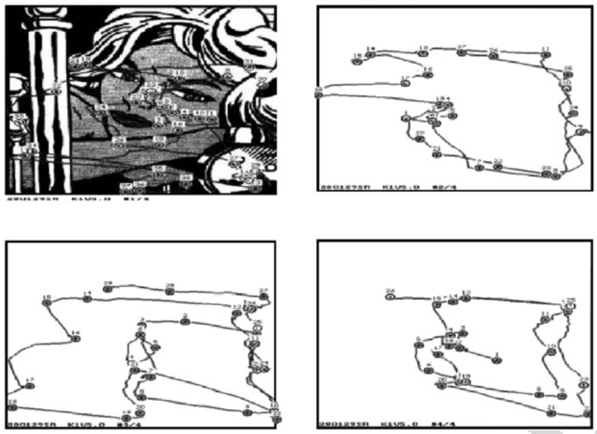


Fig. 8. (a) Upper: median Sakkade amplitude as a function of [real vs. imagery] and set. (b) Lower: example of progressive miniaturization of scanpath with imagery (R. Lichtenstein "Blonde Waiting"). First (left upper) in the viewing phase the portrait is scanned; after 5 s first imagery of the picture (right upper) is performed; after 30 s (left lower) and 60 s (right lower) follow imagery 2 and 3. The similarity between viewing and imagery scanpath and among the three imagery scanpaths is shown here. In this scanpath presentation the fixations were calculated offline, marked (circles) and numbered (adapted from Gbadamosi and Zangemeister [22]).

Also the task (Fig. 9a) of "easy" looking versus "detailed" or "recollection" indicates an influence on fixation durations with a general decrease from "easy" to "recollection", in both picture viewing and imagery scanpath, where "easy" shows the longest durations.

Fig. 9a and b show that the *imagery* scanpath (compare [22]) needs much longer duration of fixations ($p < 0.001$) compared to the real picture viewing. This was true for both the duration differences of imagery and its dependency on a particular task, with "easy viewing" showing the longest duration. The explanation of the significantly longer fixation durations for imagined pictures is given in Fig. 8a. The saccadic amplitudes become significantly ($p < 0.001$) smaller with the visual imagery, namely by about one-third of saccadic amplitudes of the real image scanpath: such that it becomes more difficult, i.e. needs more time to generate stable fixations.

Similarly, the G/L ratios show that real picture viewing is more globally done, whereas imagery is more locally performed (Fig. 10).

When we use the global/local ratio, i.e. the ratio between saccades of $> 1.1° / < 1.1°$ [1.1° threshhold] as a measure to distinguish the three *picture types* during different tasks of viewing, it appears that abstract pictures represent the most global viewing with the detailed task having the highest G/L ratio (Fig. 10a); whereas the search pictures represent the most local viewing with easy viewing at the low end of G/L ratios. A similar G/L result can be noted when we compare real viewing with imagery (Fig. 10b): realistic and abstract G/L ratios are generally higher than G/L ratios of the search task; and since saccadic amplitudes become smaller within imageries, the G/L ratio also becomes significantly smaller. All these differences are highly significant ($p < 0.01$).

4. Discussion

4.1. Homonymous hemianopia simulation and related rehabilitative aspects

Hemianopia, defined as a complete visual field defect is divided into different forms according to the site of the lesion.

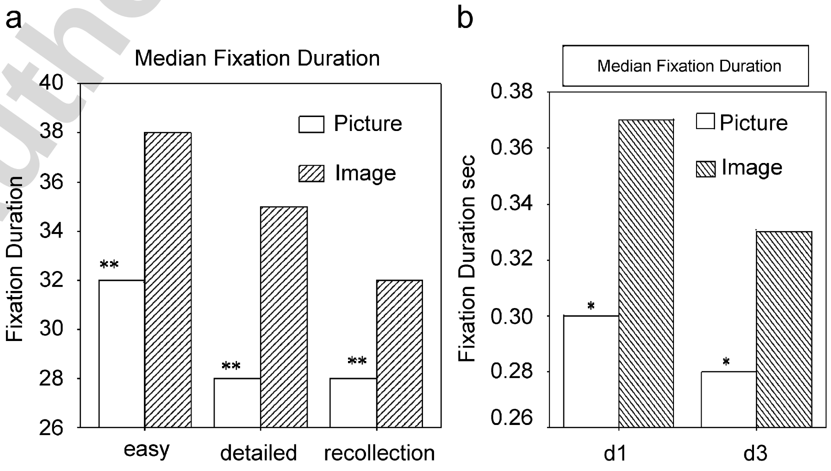


Fig. 9. Median fixation duration as a function of real vs. imagery and task (a, left) and set (b, right).

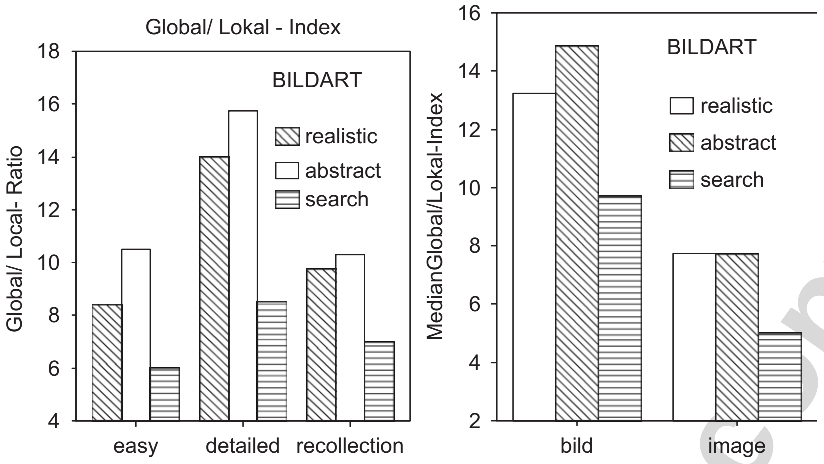


Fig. 10. Global/local ratios as a function of [real vs. imagery] and task; and of stimulus type (realistic, abstract).

The homonymous form more often shows macular sparing, leaving the foveal center of the visual field undamaged, which is responsible for the often occurring relatively adapted spontaneous recovery; a complete full hemianopia—such as we simulated it—often leads to enduring more pronounced visual disabilities: This is an obvious reason why a specific therapy in these cases is of great importance. Common etiologies of this disorder are the ischemic cerebrovascular event, followed in frequency by bleedings and trauma. Often hemianopia is associated with other cognitive dysfunctions like aphasia and visual hemineglect. Rossi et al. [32] found that more than 20% of patients with stroke treated in rehabilitation centers expose hemianopic symptoms. The impact of this sensory deficit depends on size and localization of the lesion, impairing patients in visual information processing in many ways. Hemianopia usually causes problems exploring the blind hemifield causing patients to perform hypometric, slow down head movements and generate low amplitude saccades, therefore handicapping them more or less severely in orientation and safety in everyday living. Prospective studies of the natural course of vascular retrogenicular visual field defects showed that spontaneous restitution—e.g. axon-sprouting—in the blind hemifield takes place within the first 6 months after the event and that the average visual field gain may be up to 16% in perimeter. To some degree oculomotor training strategies can compensate the sensory deficit.

Pommerenke et al. [33] found that a specific systematic exploration practice through perimetric saccade training improves visuo-spatial orientation in these patients. Furthermore, Zangemeister et al. [15,19,28,31] investigated the influence of cognitive motor gaze control strategies on the rehabilitation of visual field defects in hemianopic patients and found significant improvement in their visual behavior after taking part in a special cognitive training of gaze control.

A study of Butter et al. [10] tested visual imagery in hemianopic patients with occipital lesions using special imagery and perceptual control tasks. On the basis of their results, they postulated an impaired visual imagery in these patients because compared to a control group they performed worse in the imagery task when perceiving the stimulus ipsilateral to their visual field defect. They concluded that this finding supports the view that visual imagery involves topographically organized visual areas of the occipital lobe.

4.2. Scanpaths in hemianopic patients when compared to normal subjects

In a previous study we discovered [3,4,16] distinct characteristics of scanpaths in hemianopic patients when compared to normal subjects viewing the same stimuli suggesting a reduced extent of the image within the cognitive representation. Differential similarity measures demonstrated that the gaze sequences of the picture exploration phase exhibited less (but non-random) similarity with each other and a reduced field of view in the hemianopic patients than in normal subjects. This finding suggested a strong TD component in picture exploration: In both groups, healthy subjects and hemianopic patients, a mental model of the viewed picture evolved very soon, which substantially determined the eye movements. As hemianopic patients showed analogous results to the normal subjects we concluded that well adapted patients have a preserved cognitive representation despite their perceptual defect, which follows the same TD vision strategies in the process of viewing.

In an earlier quantitative evaluation of human scanpaths Zangemeister et al. [3,31], we compared eye movements of hemianopic patients with normal subjects' eye movements while viewing abstract and realistic pictures before and after a special training. This training included special advice concerning eye movement strategies as in the present study but also several different settings of training; also, it lasted for 14 and 28 days, respectively, with control recordings after each time span: after the training the viewed pictures were presented again. The correlated scanpaths were divided into *a priori* geometric regions of interest (ROI's) and subjective *a posteriori* ROI's. The evaluation of the scan paths was done using Markov analysis and string-editing. The results showed, despite long latencies between the time of lesion and the beginning of the training (6–12 months), that our specific rehabilitative training was significantly successful when quantified by probabilistic and sequential measurements of the resulting scanpaths. Especially the comparison of a priori and a posteriori measurements permitted a differentiation of the training effects more closely.

This result correlated to a *facilitated mobilization of information* of extra-striatal high level information: The visual information was transmitted through a quick fill of the striatal visual buffer and inside this visual buffer located *attention window* [19,20] that appeared to be opened [or enlarged] through the training. We took this as an expression of the subjective enlargement of interest through stimulation of the associative cortex. After the training, there was a strong TD component during the picture view, that alternated with a non-adapted BU component before the training. This demonstrated that it is particularly significant that the cognitive aspect of human vision in a rehabilitation of hemianopic patients has to consider special training methods.

Our here reported results in virtual hemianopic subjects are consistent with these earlier observations: Healthy subjects show quite similar oculomotor behavior when confronted with the hemianopia simulation. This is true for simple pursuit and saccadic stimuli as well as search and scanpath tasks. Therefore, TD mechanisms and the feature ring hypothesis explain the consistency and convergence of the oculomotor behavior also in normal subjects confronted with the same sensory deficit as homonymous hemianopic patients as well as their similar response to our special training.

5. Conclusion

Applying a sophisticated string analysis permits to show differentially the many significant differences that follow therapeutical masking of the foveal region during a [virtual, model] hemianopia. The visual imagery scanpath is done over a compressed mental image that needs longer fixation duration but fewer saccades than the real image. The combination of different viewing tasks with different types of pictures permits to show how TD strategies of the scanpath can be enforced or decreased by a proper combination of task and picture; this is basically influenced by the mask versus no-mask difference, with BU mechanisms becoming more important with the additional loss of foveal viewing strategies in the mask condition.

In previous studies we tried to obtain information about the consistency and reproducibility of internal visual image representations in hemianopic patients in the context of active “high-level-vision” and about the quantitative effect of training in these patients even up to 12 months after the time of lesion. The mental image of the hemianopic patients was found to mirror their visuocortical sensory deficit. Special training evidently helped in this aspect.

In this study we analyzed the degree of adaptation that normal healthy subjects show when suddenly exposed to a virtual complete homonymous hemianopia under different training conditions.

Their saccadic, scan and search path strategies showed the same consistency and reproducibility of internal visual representations as hemianopic patients in the context of active “high-level-vision”. Particularly those simulated hemianopia subjects that where well adapted with the aid of our special training did show this effect using a TD strategy when viewing targets and pictures on the side of their blind hemifield. Non-adapted subjects failed to show this effect. They stayed with a BU strategy of viewing targets on the side of their blind hemifield.

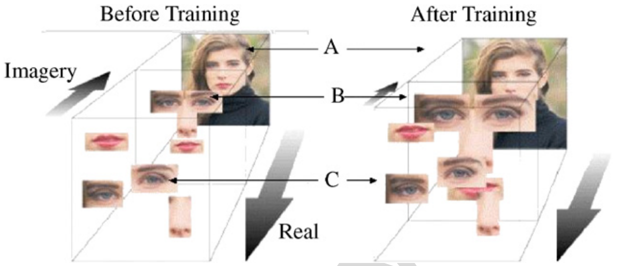


Fig. 11. Principle of visual perception and hemianopia training. *Left,* before training: The viewed image (A) will be transmitted into a striatal visual buffer (B) in a spatial format. The details will now be stored in the extra-striatal long term memory (C). *Right,* after training: The visual buffer will be filled quickly, a *rapid fill of visual buffer.* Further, the information will be released in a facilitatory manner, a *facilitated moblization of information*.

We conclude that—in addition to earlier described therapeutic tasks—hemianopic *patients* should apply our here in *healthy* subjects described additional increase of their field defect: Similarly as a “forced use therapy” as suggested by Taub [34], so that they become faster aware of the increased gaze efficiency when shifting the zero meridian of their visual field towards the side of the BHF.

From these findings we could draw three conclusions that are illustrated in Fig. 11:

Firstly, applying a sophisticated string analysis such as cRSE permits to show differentially the many significant differences that follow therapeutical masking of the foveal region during a [virtual, model] hemianopia.

Secondly, the visual imagery scanpath is done over a compressed mental image that needs longer fixation duration but fewer saccades than the real image.

Thirdly, the combination of different viewing tasks with different types of pictures permits to show how TD strategies of the scanpath can be enforced or decreased by a proper combination of task and picture; this is basically influenced by the mask versus no-mask difference, with BU mechanisms becoming more important with the additional loss of foveal viewing strategies in the mask condition.

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