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How are ocular behaviours affected by central and peripheral vision loss? A study based on artificial scotomas and gaze-contingent paradigm.

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Abstract

This study aims at understanding the effects of homogeneous visual field defects on ocular movements and exploratory patterns according to their peripheral or central location. A gaze-contingent paradigm was implemented in order to display images to the participants while masking in real-time either central or peripheral areas of the participant's field of view. Results indicate a strong relation between saccade amplitudes and mask sizes. Fixations are predominantly directed toward parts of the scene which are left unmasked. In a second set of analyses, we defined relative angle as an angle between a saccade vector and a preceding one. We show that backward saccades are more frequently produced with central masking. As for peripheral masking, we observe that participants explore the scene in a sequential scanning pattern seldom foveating back to an area attended in the previous seconds. We discuss how masking conditions affect ocular behaviours in terms of exploratory patterns, as well as how relative angles unveil characteristic information distinguishing the two masking conditions from each other and from control subjects.

Introduction

The understanding of the Human Visual System is seldom considered or modeled as a bipartite system consisting of central and peripheral vision. Central visual attention is defined as processing of data present within the fovea up to the macula (2° up to 20° of visual field [1]). It is observable through foveations (relocation of the visual scene onto the fovea via saccades to fixate particular areas), it is deemed an overt behaviour. On the other hand, the spotlight of attention can just as well set on an object of interest outside of the fovea into the periphery without eye movements, it is then said to be a covert type of attention. Central vision is the area of highest visual accuracy within the retina [2], with a diameter of approximately 10° of visual field [1]; the fovea itself measures approximately 2° and the peri-fovea 10°. Visual acuity decreases sharply as a function of eccentricity to the fovea, the peripheral field of vision displaying larger receptive fields [3, 4] and thereby lower acuity in terms of spatial frequency, colour and direction.

Saccades and fixations are ocular behaviours we will be referencing throughout this paper. A saccade is a ballistic eye movement relocating the fovea onto a new area of the scene to extract information with the highest point of acuity on the retina. In a very high proportion (99%) saccades amplitudes are below 15° of visual field [5]. Fixations are periods in-between two relocations of the gaze during which a stimulus is observed with precision. Reorienting of attention is observable by a saccade made toward a new point of interest in the scene. The choice of a new destination relies on salient attributes of the stimuli analyzed by the peripheral field of view [8]. But also on factors specific to the participant (e.g. motivation [9]). Therefore succession of saccades and fixation are linked to constant interaction between central and peripheral visions.

Gaze-contingent paradigm

In the present experiment we chose to rely on a Gaze-Contingent paradigm (GCP) to emulate artificial scotomas with normal participants. This in order to study ocular behaviours in the cases where central or peripheral vision is unavailable. A GCP [10] is an experimental paradigm in which a stimulus displayed on a screen is updated in real-time according to gaze data from an eyetracker. Such a paradigm has been used to study central and peripheral visions (e.g. [11, 12]). Central mask (i.e. blind spot, central scotoma, moving mask) prevents sampling of the scene with the fovea. Peripheral masking (i.e. spotlight, moving window) only allows sampling of stimuli by central vision. The nature of the mask can be total obstruction of the visual field or low/high-pass frequency filters, for example. The size and shape of the mask can also vary according to the perceptual span of the task at hand [11, 13]. Finally, it is also possible to create a contingent mask from a model of a defective visual field [14].

The main shortcomings of this paradigm are related to eyetracker data quality [15] and latency [16]. Regarding the second point, Loschky and Wolverton [17] advise a maximum latency of 60 ms, McConkie and Loschky [22] report visual perception as early as 6 ms after the end of a saccade.

Artificial scotomas: simulation of retinal defects

Simulating peripheral and central visual field defects in visual tasks shows interesting results, namely pertaining to saccade amplitude. Saccade amplitude will increase when masking central vision as a function of the mask size, while masking the peripheral field of view will tend to reduce saccade amplitudes according to the size of the mask. The literature shows that saccades are directed toward areas of unmodified information. This was verified in the case of low-pass [25, 26] and high-pass filtered [12], central and peripheral masks. Nuthmann & Malcolm [27] demonstrated this effect by removing colour in a stimulus in the periphery or in the central field of view.

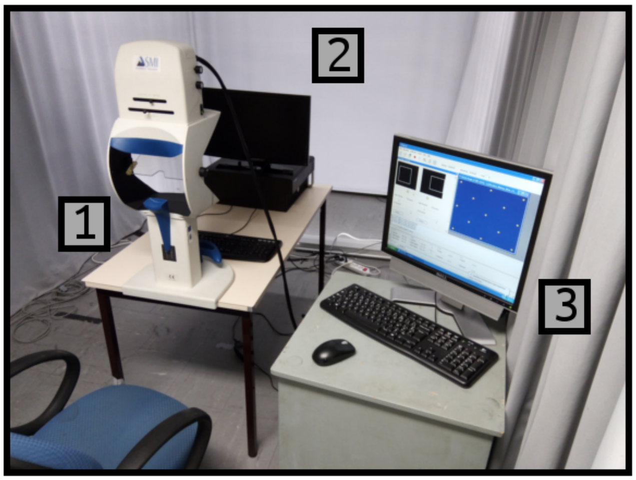
In this study we examine ocular behaviours by removing all peripheral or central information using a gaze-contingent paradigm. We also vary the size of the masks in order to measure what effects the amount of available visual information has on ocular patterns.

Method

Participants

In total 60 participants were recruited (39 women, mean age: 28 years old) via a mailing-list reaching students of Nantes University. All participants were compensated for their time. Normal or corrected-to-normal vision was verified by a Monoyer test and normal colour discrimination with the Ishihara color blindness test ; individuals wearing glasses were excluded from the study because of the difficulty the eyetrackers generally have to track their gaze. The dominant eye was also determined. All participants gave their written consent before beginning the experiment.

Figure 1. Experimental set-up used in this experiment. The eyetracker (1) is connected to the gaze processing computer (3). The display computer (2) updates on-screen stimuli with gaze data received from (3).



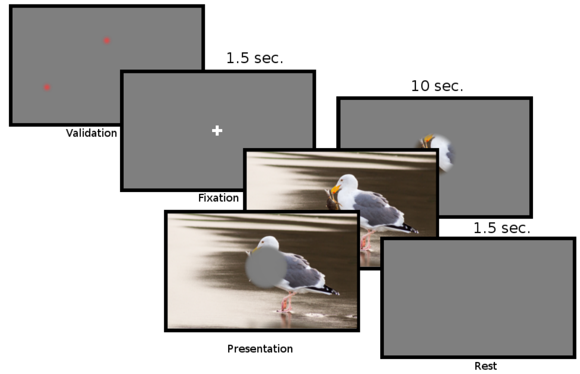
Apparatus

Stimuli were displayed on a screen of 1920 by 1080 pixels (23in., 144Hz). In order to measure participants' gaze position in real-time we rely on an SMI Eyetracker (Hi-Speed, 500Hz). The data acquisition is binocular but only the dominant eye's positions are involved in updating the stimuli in the present paradigm. This gaze-contingency set-up requires two independent computers (figure 1). The first one is operated by the experimentalist, it is linked to the eyetracker to retrieve and process gaze data. The second one displays stimuli to the participants, updating a displayed stimulus according to on-line data sent from the first computer. The display computer is run by an NVIDIA GTX 1080 GPU and an Intel E5-1650 CPU. We designed this set-up to reduce the maximum latency between an ocular behavior and the update of on-screen stimulus, achieving a maximum latency of 13 ms.

Stimuli

21 pictures of indoor and outdoor scenes were used as stimuli. All photographs are licensed under Creative Commons, coloured and HD (1920x1080, 31.2° by 17.7° of visual field). Six images were set aside for a training phase. The stimuli were selected for their varied characteristics (complexity of the scene, number of objects of interest).

Figure 2. Progress of a trial. Beginning with a set of validation points to check the eyetracker's accuracy. A fixation cross then appears, disappearing after approximately 1.5 sec. An image appears next for 10 sec., in one of the three mask type conditions and one of the three mask size conditions (not represented here). A trial ends with a resting period of 1.5 sec.



Experimental design

A gaze-contingent paradigm was implemented to study ocular movements pertaining to central and peripheral visions (figure 2). The stimuli showed to participants were updated dynamically with gaze data from the eyetracker. A software was written to display, modifying the original stimulus, a circular gray mask centered at participants' gaze positions, masking either central or peripheral area. Our goal was to replicate central and peripheral retinal lesions and their resulting loss of vision. In this context, we created a masking experimental condition comprised of two modalities: a central mask, preventing sampling of the scene with central vision, and a peripheral mask which only allows perception of a foveated area. In order to study the relationship between the size of the lesion and ocular behaviours a second condition varies the diameter of the masks (3°, 5°, 7°, 9°) from approximately the size of the fovea up to the size of the peri-fovea. A control group experimented the original stimuli without gaze-contingent masking. Both masking and size conditions are varied randomly, first within-subjects and second between-subjects. The 60 participants were divided into 4 groups each experiencing one of the 4 different mask sizes.

Procedure

After two visual tests (acuity and colour), participants are told to explore freely each image. Following a training phase, 15 images are displayed in 3 consecutive runs separated by one-minute pauses. Each image is displayed once per run in one of the two masking conditions plus the control one. A calibration of the eyetracker is scheduled at each run start. A validation of the calibration is performed before each trial, triggering a new calibration if mean euclidean distance from validation points is above 2.5° (above average human fixation stability [6], taking into account eyetracker's precision and validation dot's size). Participants have to fixate a cross in the middle of the screen for at least 500ms, ensuring that scene exploration begins by a fixation at the center of the stimulus. Failing this fixation check will trigger a calibration phase, otherwise a stimulus is displayed for 10 sec.,

Means and standard deviations are reported for fixation duration, fixation number and saccade amplitude, for mask types.

	Fix. dur. (ms)	Fix. number	Sacc. ampl. (°)
Central	289 (153)	24.78 (7.48)	6.53 (4.45)
Periph.	307 (182)	21.69 (8.47)	3.32 (2.46)
Ctrl.	321 (176)	21.85 (6.43)	5.35 (4.09)

then disappears for a 1.5 sec. inter-trial rest.

Data preparation

Data were acquired and saved unfiltered. A denoising filter was applied to raw data in order to obtain a better segmentation into fixations, saccades and blinks by a velocity-based parsing algorithm [29]. Out of 2,700, a total of 270 trials were removed because of poor data quality (owing to the recording or blink-like artifacts). 3622 fixations were removed for lasting less than 100 ms, 2121 were removed for lasting longer than 1000 ms. 4 saccades longer than the diagonal of the screen were deemed aberrant and removed from our dataset. The following analyses are based on the remaining 55,314 fixations and 54,766 saccades.

Results

Three dependent variables (fixation duration, fixation number, saccade amplitude) were studied with Linear Mixed Models (LMMs), considering mask types (Control, Central, Peripheral) as a within subjects variable; mask diameters (3°, 5°, 7°, 9°) as a between subjects variable; images as a random effect. Saccade amplitude and fixation duration are log-transformed for models residuals to reach normality. Main and interaction effects are reported if significant. In post-hoc analyses t-tests are reported, as well as Cohen's d [30, 31].

Fixation duration

A mixed-effect model of fixation duration shows a main effect of mask type ($F(2,54496) = 13.37; p < 0.0001$). We observe significant differences between mask types ($ps < 0.0001$), though because of high standard deviation only the comparison between control and central masking shows a marginally small effect ($d = 0.19$).

Fixation number

We can report a main effect of mask type ($F(2,1611) = 19.21; p < 0.0001$). Central masking shows a significant increase ($ps < 0.0001$) in number of fixation compared to control ($d = 0.42$) and peripheral masking ($d = 0.39$) (table 1).

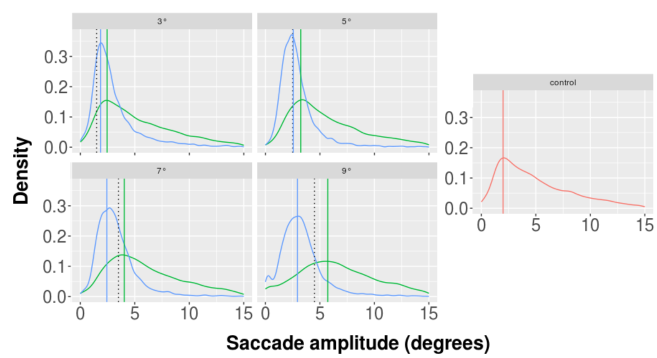
Saccade amplitude

An analysis of saccade amplitude shows a main effect of mask type ($F(2,53948) = 573.47; p < 0.0001$) and a significant interaction effect ($F(6,53948) = 3.42; p < 0.005$). We report significant differences between all mask type means ($ps < 0.0001$) and a small effect between control and central masking (d=0.30), a medium effect between control and peripheral masking ($d = 0.50$) and a large effect between both masking types ($d = 0.86$). Compared to central masks, peripheral masks show significantly reduced means ($p < 0.0001$) across mask sizes (3°: $d = 0.68$,

Means and standard deviations are reported for saccade amplitudes according to mask types and sizes.

Mask type	Mask radius	Mode	Mean (Sd)
Central	1.5°	2.46	5.88 (4.46)
	2.5°	3.24	6.31 (4.43)
	3.5°	4.03	6.64 (4.37)
	4.5°	5.73	7.32 (4.45)
Peripheral	1.5°	1.85	3.36 (2.99)
	2.5°	2.56	3.07 (2.20)
	3.5°	2.44	3.40 (2.22)
	4.5°	2.94	3.43 (2.39)
Control		1.99	5.35 (4.09)

Figure 3. *Probability density functions of saccade amplitude as a function of mask type and size. The mask radius is displayed as a black dotted line. Solid lines represent modes of the distributions displayed in the same colour as its target: central masking in green, peripheral masking in blue, control data in red.*



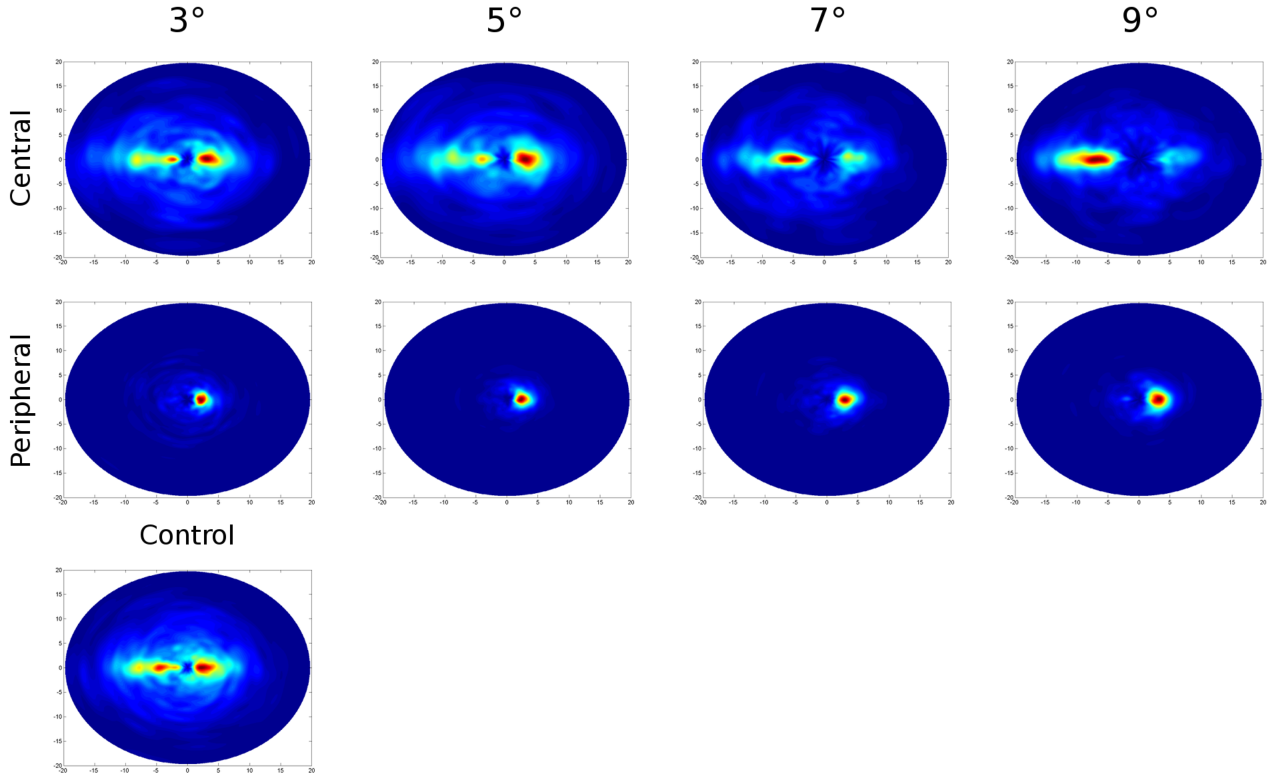
5°: $d = 1.02$, 7°: $d = 0.91$, 9°: $d = 0.89$). Similarly, mask types compared to control data across mask sizes show significant levels of difference ($ps < 0.0001$) with d values above 0.3, apart from comparison with central masking in the cases of mask sizes 3° ($d = 0.13$) and 5° ($d = 0.29$). In central masking condition, saccade amplitudes in sizes 7° and 9° are significantly greater than for size 3° ($ps < 0.0001$, $ds > 0.2$).

Mean and mode of saccade amplitude according to mask sizes across types are reported in table 2. Refer to figure 3 for an illustration of saccade amplitude distributions. The distributions are positively skewed. In the case of central masking, we observe, as mask size increases, a reduction of skewness and kurtosis as the mode of the distributions stays located outside of the mask. As for peripheral masking, the high kurtosis displayed and mode localisation place a high density of saccades very close to the mask's edge for mask diameters 3° and 5° and well within the visible area of the scene for larger diameters.

Relative angles

In order to investigate ocular patterns we define as relative angle the angle between two saccade vectors. Contrary to absolute angles which reflect the direction of a saccade relative to a horizontal axis, relative angles provide more information. A saccade at a relative angle of 0° to its preceding neighbour would be

Figure 4. The polar graphs represent amplitude of saccades and their direction relative to the previous one as a function of mask type and size.



going in the same direction, thus going further on the same route. A relative angle of 180° means a saccade was made in the direction of the preceding one (backward saccade). As a qualitative analysis of relative angles we note (figure 4) that in the control condition participants display a somewhat horizontally homogeneous distribution, they were as likely to foveate back toward a previous fixation location as they were to explore further away from it. In the case of central masking two patterns emerge: for mask sizes 3° and 5°, saccades are made in a manner similar to control data. In the case of larger masks (7° and 9°) a high density of backward saccades are observed. As for peripheral masking, we notice a majority of saccades carrying on the same direction as the previous one. In both central and peripheral masking the number of saccades made within the masks are very limited.

Discussion

In this experiment we aimed at understanding how losing central or peripheral vision affected exploratory patterns by varying the size of the available field of view. We showed stimuli to normal participants obstructing the central or peripheral field of view in a gaze-contingent paradigm and gathered results pointing at distinct exploratory patterns and saccadic/fixation parameters.

Central masking

We observed shorter fixations in the case of central masking, as well as an increased number of fixations possibly as a result of repetitive backward saccades. Saccade amplitude were globally increased, placing the majority of saccades outside of the mask toward unaltered portions of the scene. In the smallest mask size condition it is hypothesized that foveated areas contained enough information for this particular task. Thus reducing the number and backward saccades, producing a polar graph of relative angles closer to control data. Relative angle plots show a high number of backward saccades. We hypothesize the following behaviour: an increased number of backward saccades can be seen as an attentional drive toward a zone that is deemed salient but cannot be perceived when foveated. The Inhibition Of Return mechanism is may not be activated due to a lack of information, leading some participants to go back and forth between salient elements.

Peripheral masking

Peripheral masking led to significantly reduced saccade amplitudes. Fixations appear to be directed at the edge of the mask, maybe in an effort to maximize the amount of information sampled by the next fixation, moving one's gaze as far as possible within the observable scene. Regarding smaller peripheral mask sizes (3° and 5°), the mode of the saccade amplitude distributions are not within the unmasked area, contrary to larger sizes. Two hypotheses can be formulated relative to this observation. First, it is possible that saccades of amplitude smaller than the masks radius (1.5° and 2.5°) are not detected as saccades as they would fall below our algorithm threshold (per saccade velocity) and be categorized as natural dispersion within a fixation. A second explanation would be that participants do not, in these experimental conditions, plan saccades smaller than a fixation's usual dispersion. Finally, by masking peripheral vision and leaving only a foveal area unmodified, we noticed relative angles largely made toward the same direction as the previous saccade. This behaviour resembles a scanning pattern where participants plan fixations to fall within the centred disk of vision, each one carrying on generally in the same direction as the previous one.

Conclusion

In this study we were able to extract ocular patterns. We showed discriminating characteristics of ocular movements according to masking type (central or peripheral). Within our selected range of mask sizes results mostly pertained to saccade amplitudes as the most significant variable differentiating ocular movements. We highlighted amplitude increasing with mask size when a central mask was applied. Overall, when experiencing a peripheral mask saccade amplitudes were significantly decreased compared to the other mask condition and control data. We chose to explore ocular movements according to a small range of mask sizes. In this regard our results hold for somewhat small masks, as big as the peri-fovea (9°). In conclusion, relative angle analysis unveils details about exploratory ocular patterns that are lost by saccade amplitudes alone. It allowed us to reveal peculiar ocular patterns occurring when masks were applied. Particularly, we observed an important amount of backward saccades when masking the central field of view. We also noticed with peripheral masking that scenes are explored with saccades the size of the mask's radius, each generally directed toward the same direction as the previous one.

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