EFFECTS OF MÜLLER-LYER ILLUSION ON THE ACCURACY OF PRIMARY SACCADES AND SMOOTH PURSUIT EYE MOVEMENTS

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Abstract. The goal of the present investigation was to support or to oppose the two-visual-system (vision–for perception and vision-for action) hypothesis. Since illusions might be the subject of misinterpretation and the loss of presented information, we decided to examine how Müller-Lyer (M-L) illusion affects accuracy of double-step saccades and smooth pursuit eye movements and compare these results with those obtained during perceptual judgment of the length of the shaft of M-L illusion. Experimental investigation revealed that the primary saccades elicited in double-step mode were mostly affected by the M-L illusion. The position errors of the primary saccades elicited in the reflexive mode were affected by 4% for wings-in illusion and by 3.6% for wings-out illusion comparing with the 0.25% and 0.1% for the saccades elicited in the voluntary mode. The position errors of complete saccades (0.14% and 0.02%) and tracking errors obtained during the smooth pursuit (0.11% and 0.05%) were negligibly small. Nevertheless, experimental results obtained during perceptual judgment of M-L illusion were substantially larger - 14% and 10%, respectively. Our experimental investigation of the accuracy of saccadic and smooth pursuit eye movements elicited to the stimulus with M-L illusion unfolded that the visuo-motor system is able to resist to the illusory stimulus and supported the two-visual-systems hypothesis. Obtained results have demonstrated that the main parameter, which plays the most important role on the precision of visuo-motor behavior, is the uncertainty of perception of the shape and the position of the illusionary stimulus.

Keywords: visuo-motor system; double-step saccades; smooth pursuit eye movements; illusion; dynamic illusion evaluation.

1. Introduction

At the beginning of the investigation of visual illusions, only one method, that is the method of perceptual judgments, was used. In these experiments, the effect of misperception of size, length or angle of the objects, enriched with geometrical illusion, was evaluated. Subjects were examined in the simple way. The target was to observe how large the differences between the illusionary perception and real geometrical parameters were and to explain what deceives the vision. The nature of pictorial illusions was investigated by A. Bulatov and A. Bertulis. They developed a model based on centroid (distribution of masses) of illusory patterns of various spatial structures, which was integrated in the visual pathways [1]. That causes mismatching of extent of illusory patterns.

Further investigation of pictorial illusions was performed together with motor actions [2]. It was noticed that the effect of a visual illusion, evaluated during perceptual judgment, differed from the effect of the adequate illusion, which was made with illusory pattern during visuo-motor or/and visuo-manual action. Many experiments proved that illusions evident in subjective reports of stimulus size, length or angle often had little influence on visually guided actions [3].

Now it is widely recognized that visual information from frontal eye field is divided in two visual streams (subsystems): vision-for-perception and

vision-for-action. The presence of these two channels can be functionally interpreted as a division of labor between two subsystems. Specifically, the dorsal subsystem specializes in the visual guidance of action, whereas the ventral subsystem specializes in object perception and recognition. Evidence for the two-visual-systems hypothesis has come from studies comparing the effects of illusions on perceptual judgments and visuo-motor behavior. These two kinds of behavior are mediated by the modality of response: subjective or perceptual-motor. Difference between the stimuli for perceptual and motor tasks could be explained comparing the influence of Müller-Lyer (M-L) illusion on perceptual judgment and oculo-motor action directing the gaze towards the wings of the shaft in dynamic conditions.

In the papers by Knox and Bruno [3] as well McCarley and Grant [4], the estimation how much the length of M-L stimulus would be biased by the illusion during saccadic eye movements was performed. The authors of the above mentioned papers examined the amplitudes of the reflexive and voluntary eye jumps to the corners of the arrows of M-L illusion. They used short presentation of the stimulus (0.2 s) and found that both types of saccades could be strongly affected by the illusion. The effect of the M-L illusion on reflexive saccades was comparable to that usually observed with perceptual judgments (an effect size of 22 %), whereas the effect on voluntary saccades was smaller (11%). An important difference between reflexive and voluntary saccades is due to the fact that voluntary saccades were elicited in memory-guided performance. Nevertheless, investigation of the influence of M-L illusion on the primary saccades, elicited in double-step mode, and on the smooth pursuit eye movements have not been researched yet.

Since illusions might be the subject of misinterpretation and the loss of presented information, we decided to examine how M-L illusion affects accuracy of double-step saccades and smooth pursuit eye movements. The goal of the present investigation was to support or to oppose the two-visual-system hypothesis and to unfold the way the visuo-motor system is able to resist the stimulus of M-L illusion.

2. Method

In experiment 1, we examined the influence of the illusion on the amplitudes of voluntary and reflexive saccadic eye movements elicited to the arrows of M-L illusion (point A, B, and C, D in Figure 1). In experiment 2, we measured the accuracy of smooth pursuit eye movements when subjects tracked the arrow stimulus (point E in Figure 2) moving from left to right and back with three constant speeds 5, 10 and 20deg/s. To compare the effect of visual illusion on the accuracy of saccadic and smooth pursuit eye movements with the results, obtained during

perceptual judgment, experiment 3 was conducted. In this experiment the same subjects as in experiments 1 and 2 perceptually evaluated the length of the shaft of M-L illusion.

During the first two experiments, the movements of both eyes were recorded with eye tracker "EyeGaze System" produced by "LC Technologies Ltd". Healthy subjects, 21 - 48 years old, were recruited after informed consent. Among the five subjects, three authors participated in the experiments. None of the subjects showed any visual, oculo-motor or oculo-manual pathology. Subjects had normal visual acuity without glasses. All calculations were processed using standard MATLAB functions.

The shape and dimensions of M-L illusion used in experiment 1 are shown in Figure 1 and the moving arrow used in experiment 2 is shown in Figure 2. All dimensions in Figure 1 and Figure 2 are shown in angular degrees of the subject's gaze which fit the size of the illusion presented on the computer screen.

During the first part of experiment 1, when voluntary saccades were examined, subjects were asked to direct their gaze voluntarily from the left arrow to the right and back. In the second part, when reflexive saccades were investigated, arrows of M-L illusion were alternatively switched on and off and subjects were asked to direct their gaze towards the flashing stimulus. As the reference stimulus without illusion for voluntary and reflexive saccades, the same shape of M-L illusion with the wings of the arrows turned in vertical line was used.
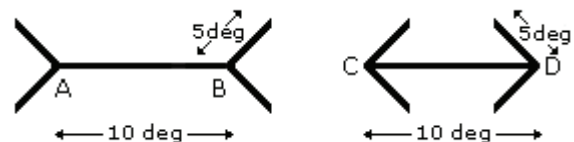

Figure 1. Presentation of the shape and dimensions of M-L illusion used in experiment 1 to investigate the accuracy of voluntary and reflexive saccades
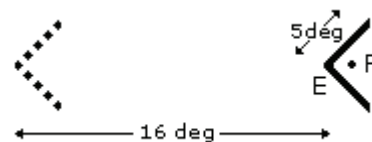

Figure 2. Presentation of the stimulus moving forward and backward used in experiment 2 to investigate the accuracy of smooth pursuit eye movement

3. Experimental results

Distributions of position errors of voluntary and reflexive saccades elicited to the stimulus of M-L illusion are presented in Figure 3 (A, B and C) illustrates data for voluntary and (D, E and F) – for

reflexive saccades. B and E distributions in Figure 3 represent the position errors for "wings-out" stimulus and C and F represent data for "wings-in" stimulus of M-L illusion. Notation n in Figure 3 represents number of trials used in calculations, μ and σ – means and standard deviations of the distributions.

Distributions A and D represent reference data of position errors obtained without illusion. Experimental data for voluntary and reflexive saccades illustrate that saccadic eye movements were quite precise and not affected by the illusion. Moreover, as it was predicted, the voluntary saccades were more precise than reflexive. In the experiment with voluntary saccades, the shaft and the wings were seen all the time during eye jumps, therefore the subjects using visual memory were able to match up their gaze to the ends of the shaft. In the experiment with reflexive saccades, arrows, situated at the ends of the shaft, were flashing, therefore the subjects could see the stimulus of M-L illusion only for a short time. The means of position errors of reflexive saccades were 0.02 deg (0.2%) for "wings-in" stimulus and 0.14 deg (1.4%) for "wings-out" stimulus. On the contrary, the means of position errors of the voluntary saccades were negligible small.

Comparing experimental data with the results obtained during perceptual judgment (around 10%), we can conclude that the effect of the visual illusion on the amplitudes of saccadic eye movements was small.

It is obvious that saccadic eye movements execute eye jump in two steps: primary and corrective (secondary) saccades [5]. Normally primary saccades take the eye 90 % of the way to the target, followed by 10% corrective saccade.

Experimental investigation of primary and corrective (double-step) saccades has revealed that primary saccades can be either too small (hypometric) or too large (hypermetric) comparing them with the real target position. Majority of primary saccades are hypometric, and they represent a normal strategy adopted by saccadic system so that any subsequent corrective saccade requires only computation of amplitude, but not direction [6].

The distributions of the position errors of primary saccades differ from the conditions with either stationary targets (voluntary saccades) or jumping targets (reflexive saccades) they were elicited [7]. The distributions of position errors of primary saccades made between stationary targets were almost symmetrical, whereas the distributions related to the jumping targets condition were skewed in the direction of undershoot.

Analyzing two-visual-system hypothesis, the control system of saccadic eye movements attracts large interest. Neurophysiology of eye saccades substantially differs from arm movements which are usually controlled by the vision. Primary saccades, executed towards the new targets, are not precise [6]. They are affected by the poor vision of the stimulus,

which, before the eye jump, is focused on the periphery of retina, where the amount of position receptors is small. Moreover, the precision of primary saccades is influenced by motor error of the muscles of the eye-globe. Secondary saccades are quite precise. They eliminate the error which was left by the primary saccade and put the gaze on the target.
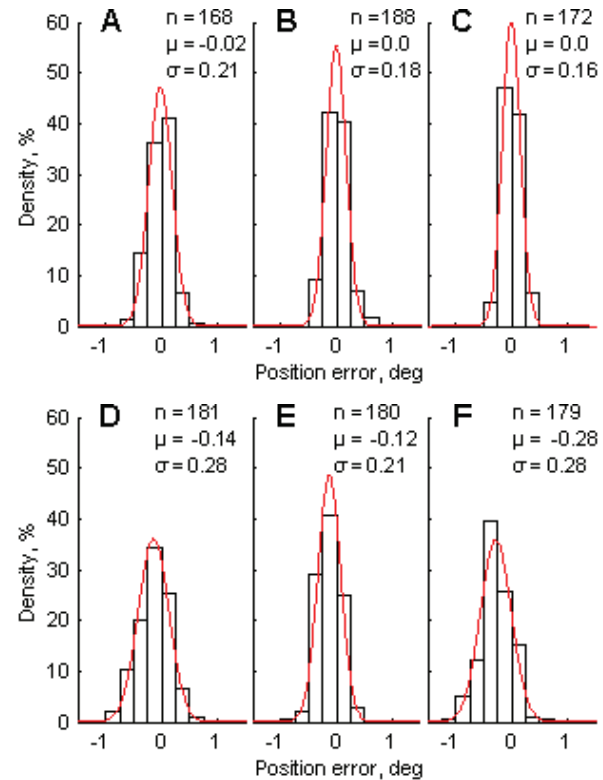

Figure 3. Distributions of position errors of voluntary (A, B, C) and reflexive (D, E, F) saccades for "wings-out" (B, E), "wings-in" (C, F) stimulus of M-L illusion and without illusion (A, D)

The investigation of the results of voluntary and reflexive saccades, obtained in experiment 1, supported the understanding that complete saccades are not strongly affected by the illusion. Subjects were able to direct their gaze to the ends of the shaft of M-L illusion. The question about the influence of M-L illusion on the primary saccades is still open and, in our opinion, never analyzed and reported.

Distributions of position errors of primary saccades elicited to the stimulus of M-L illusion in the voluntary and reflexive modes are presented in Figure 4. In this figure A, B and C illustrate experimental results of the primary saccades elicited in the voluntary mode and D, E and F – in the reflexive one. B and F distributions in Figure 4 represent the position errors for "wings-out" stimulus and C, F represent data for "wings-in" stimulus of M-L illusion. Distributions A and D represent reference data obtained without illusion. Notation n in Figure 4 represents number of trials used in calculations, μ and σ – means and standard deviations of the distributions.
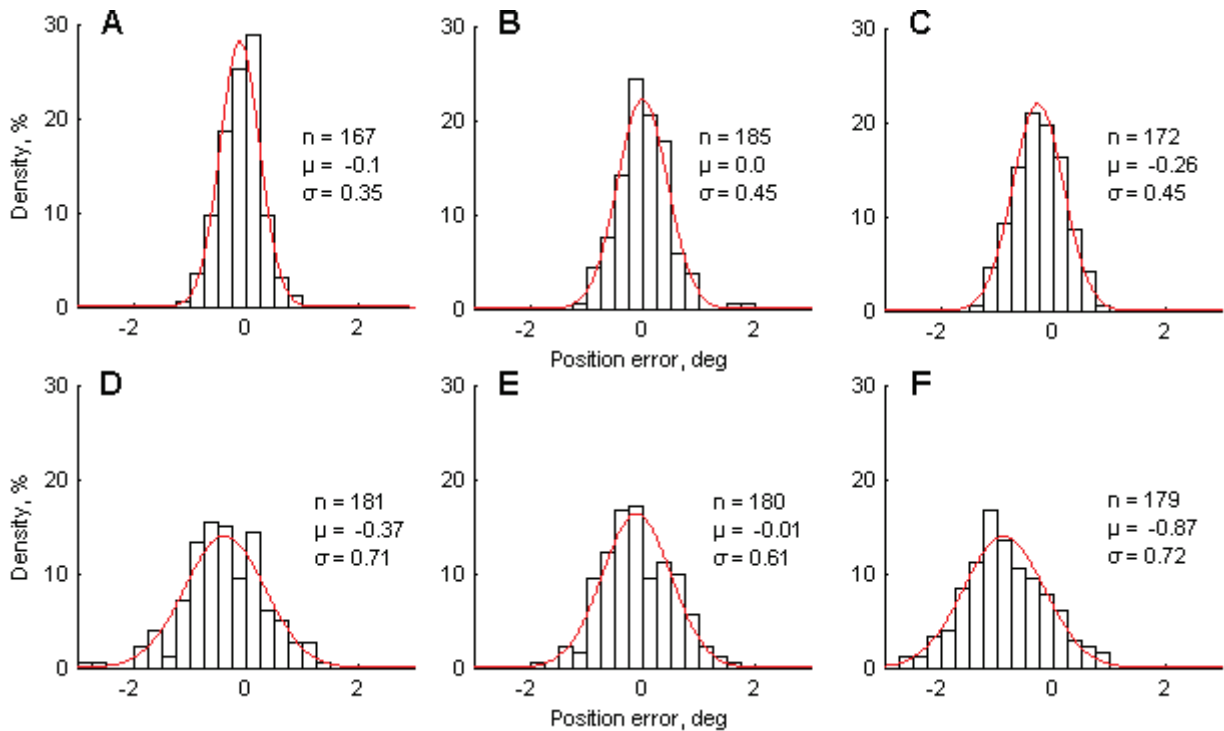
Figure 4. Distributions of position errors of primary saccades elicited in the voluntary (A, B, C) and reflexive (D, E, F) modes to the "wings-out" (B, E), "wings-in" (C, F) stimulus of M-L illusion and without any illusion (A, D) are displayed

Analyzing distributions of position errors of primary saccades, presented in Figure 4, we can see that primary saccades are less scattered than complete saccades. Standard deviations σ for complete saccades are in the range of 0.16 – 0.28 deg comparing with range 0.35 – 0.72 deg for primary saccades. Distributions of position errors of primary saccades elicited in the reflexive mode (σ = 0.61-0.72), like distributions of position errors of complete saccades, also executed in reflexive mode (σ = 0.21-0.28, see Figure 3), are more scattered than primary and complete saccades, executed in the voluntary mode (σ = 0.35-0.45 and 0.16-0.21, respectively). The main result of the investigation of primary saccades finds that M-L illusion mostly affects those primary saccades, which were elicited in the reflexive mode. Comparing the experimental data of primary saccades elicited in the reflexive mode with the results obtained during perceptual judgment, we can conclude that during the perceptual judgment the effect of the visual illusion was substantially strong: 3.6% comparing with 10% for "wings-in" stimulus and 4% comparing with 14% for "wings-out" stimulus of M-L illusion.

In order to investigate the effect M-L illusion in dynamic conditions we conducted experiment 2 with the stimulus moving forward and backward in the horizontal direction. Subjects were asked to pursue the arrow (displayed in Figure 2) moving with three constant velocities: 5, 10 and 20 deg/s.

It is widely recognized that the smooth pursuit eye movements demonstrate tracking error and delay even if the stimulus is not susceptive to the illusion [8]. Therefore, in order to evaluate the effect of M-L illusion we calculated the difference of the position errors obtained during tracking the stimulus with "wings-in" and "wings-out" illusion and reference target in the way illustrated in Figure 5.

The means μ and standard deviations σ of the tracking errors between the averaged recordings of the smooth pursuit eye movements obtained during tracking the stimulus with illusion and reference target were calculated and placed in Table 1. There we can see that the tracking errors were slightly affected by the illusion only for higher velocities. For example, for target velocity 20 deg/s, the differences of the tracking errors between the "wings-out" illusion and the reference target were 0.11 deg and between "wings-in" illusion and reference target – 0.18 deg. For the target velocity 10 deg/s, these values were even smaller: 0.05 deg and 0.11 deg respectively. The comparison of the experimental data of the tracking errors with the subjective length estimates of the shaft of M-L illusion, have proved that smooth pursuit eye movements are poor instrument for evaluation of the effect of illusion.
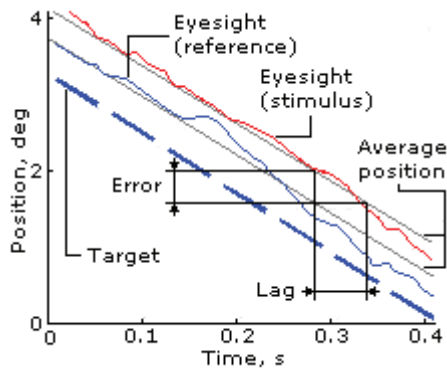
Figure 5. Presentation of the tracking error calculated between the averaged recordings of the smooth pursuit eye movements obtained during tracking the stimulus and the reference target

Table 1. Means and standard deviations of tracking errors obtained during the pursuit of the moving stimulus with illusion and reference target, n – number of trials

Velocity deg/s	n	No illusion		wings-out illusion		wings-in illusion	
		μ, deg	σ, deg	μ, deg	σ, deg	μ, deg	σ, deg
5	30	0	0,1	-0,05	0,07	-0,02	0,09
10	60	-0,13	0,13	-0,08	0,15	-0,24	0,12
20	120	-0,44	0,32	-0,31	0,3	-0,62	0,23

The extent of the illusion obtained during perceptual judgment (experiment 3) of M-L illusion (Figure 1), was 14% and 10% for wings-in and wings-out stimulus.

4. Discussion and Conclusions

The purpose of these experiments was to investigate whether there were systematic differences between the effects of M-L illusion on saccadic and smooth pursuit eye movements and on the perceptual judgments. They were motivated by the claim that reflexive saccades might be influenced by M-L illusion at the same extent as the perceptual judgment [3]. Moreover, as far as our knowledge goes the primary saccades, elicited in double-step mode, and the smooth pursuits together with M-L illusion haven't been investigated.

The obtained results have revealed that the primary saccades elicited in the reflexive mode were mostly affected by the M-L illusion. The position errors of primary saccades elicited in the reflexive mode were 4% for "wings-in" illusion and 3.6% for "wings-out" illusion comparing with the 0.25% and 0.1% for the saccades elicited in the voluntary mode. The position errors of complete saccades (0.14% and 0.02%) and the tracking errors obtained during smooth pursuit (0.11% and 0.05%) were negligible small. Nevertheless, experimental results obtained during the perceptual judgment of M-L illusion were substantially larger - 14% and 10% respectively.

Our findings disagree with the results presented by Knox and Bruno [3] as well McCarley and Grant [4]. The authors noted that reflexive saccades were affected by M-L illusion by 22%. Adequately, the results obtained in our research are 0.14% and 0.02%. From our point of view, the discrepancy of the results was obtained due to the short time (0.2 s) of exposure of M-L stimulus used in the previous experiments. Therefore, reflexive (also voluntary) saccades examined in those experiments were executed in the memory-guided conditions while our experiments were executed during the active vision. This let us conclude that the time of exposure of the stimulus was the dominant parameter affecting visuo-motor action and played the most important role on the precision of saccades.

The next factor, which is important when analyzing the influence of M-L illusion on visuo-motor action, is the site of the retina where the illusory stimulus is projected. Due to density of the distribution of receptors on the retina, the best perception of the stimulus is at the centre (fovea) and decreases towards the periphery. These two factors of the illusory pattern – time of exposure and the distance from the fovea – are the most important parameters affecting uncertainty of perception of the shape and the position of the stimulus. In the conditions of uncertainty, the visual system accepts illusory stimulus as centroid which is the centre of the mass of the figure [1]. The centre of the mass of M-L illusion is marked as F in Figure 2.

If it is accepted that the perception uncertainty of the shape and the position of the stimulus affects saccade amplitude, then our results could be easily compared with the previous studies and explained. Eye jumps (saccades) were performed under the conditions when subjects were switching their gaze from one stimulus to another. So, first stimulus, at which subject's gaze is directed, is projected on the fovea and accepted quite well (uncertainty is small). Second stimulus, which appears far in the periphery, would be accepted with larger uncertainty of perception. If time of exposure of new stimulus is only 0.2 s (time, during which eye jump do not start), perception uncertainty would be increased even more. Under such conditions, the eye jump would not be precise and could not be corrected at the end of saccade due to the absence of visible stimulus. In our experiments with reflexive and voluntary saccades to the visible stimulus, complete saccades, elicited in double-step mode, due to corrective saccade were precise and therefore were not affected by the M-L illusion. For this reason, our investigation was focused on primary saccades, which were always elicited in the conditions of the uncertainty of stimulus perception [5]. These primary saccades were mostly affected by the illusion, which had been expected before the research was carried out. Amplitudes of primary saccades comparing with control (without ill.)

were 4 % smaller for "wings-in" illusion and 3.6 % larger for "wings-out" illusion.

Analyzing experimental results of the smooth pursuit eye movements, it can be concluded that practically they were not affected by illusion. During smooth pursuit, the stimulus was projected on the fovea all the time. Therefore the uncertainty of perception of the shape and the position of the stimulus were small and the precision of pursuit was quite high.

Our experimental investigation of the accuracy of saccadic and smooth pursuit eye movements elicited to the stimulus with M-L illusion revealed that the visuo-motor system is able to resist to the illusory stimulus. The obtained results support two-visual-systems hypothesis. The main parameter, which affects the precision of visuo-motor behavior mostly, is the uncertainty of perception of the shape and the position of the illusionary stimulus. It can be stated in short: if pictorial illusions were presented for vision quite clear, the visuo-motor action would be precise and correct.

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