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The Frequency of Saccades Correlates to Peak Velocity in Symmetrical Disparity Vergence

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***Abstract*- A pure vergence stimulus requires the two eyes to turn equally inward or outward theoretically resulting in a pure symmetrical vergence response. However, saccades, a rapid conjugate eye movement, are frequently observed in vergence responses. This investigation sought to systematically quantify whether the occurrence of saccades within symmetrical vergence responses is correlated to vergence peak velocity. Eye movements are quantified using a limbus tracking system from three subjects. Symmetrical convergence and divergence 4° step responses with an initial position located at far or near which are known to evoke different peak velocities are analyzed. Data are quantified via peak velocity. A saccade detecting algorithm is utilized to quantify the frequency of saccades in the transient portion (first second) of vergence responses. Near convergence responses are slower than far convergence and far divergence responses are slower compared to near divergence movements. The occurrence of saccades is negatively correlated to vergence peak velocity. When the velocity is slower, the number of saccades increases. This study suggests that the brain may initiate a saccade to facilitate a slow vergence movement, potentially to allow object recognition before binocular fusion.**

Keywords- vergence; saccade; version; disparity vergence

INTRODUCTION

During natural viewing conditions, both vergence and version eye movements are intermixed to acquire visual information. Vergence is a disjunctive eye movement that rotates the eyes inward (convergence) or outward (divergence) to project the line of sight onto the fovea. The vergence system allows humans to achieve and maintain single binocular vision at different spatial depths. Horizontal saccades are a type of version movement which moves the eyes in the same direction to quickly shift gaze between left or right visual field (typically used while reading).

When a person is presented with a purely symmetrical vergence stimulus along the midline, the theoretical eye movement is a pure vergence response where the two eyes should turn equally inward or outward. However, saccades are frequently observed within the transient portion of vergence movements. From the literature, saccades are reported to increase the peak velocity of vergence [1] and saccades are easily identified because their dynamics are approximately an order of magnitude faster than vergence [2].

Vergence peak velocity is dependent on direction and initial position. Using the Hodgkin-Huxley equation for membrane dynamics, Patel and colleagues show that even when the model parameters for convergence and divergence are the same, divergence responses at far will be slower than the divergence responses at near and convergence responses at near will be slower than those at far [3, 4]. To test our hypothesis that saccades will occur more frequently when vergence peak velocity was slower, we designed a within subject experiment which contained both convergence and divergence movements with different initial positions. The peak velocities of these movements should vary depending upon direction (convergence versus divergence) and initial position (near versus far).

The purpose of this paper is to investigate if the occurrence of saccades is greater when vergence peak velocity is slower compared to faster vergence movements and determine if peak velocity and frequency of saccades are correlated. For example, we hypothesize that near convergence steps will have slower peak velocity compared to far convergence steps; therefore, more saccades will be detected during the near convergence steps compared to far convergence step and vice versa for divergence. We hypothesize that the brain compensates for slower vergence peak velocity by initiating a saccade to recognize the object more quickly.

METHODOLOGY

A. Subjects:

Three subjects (age 22-32) participated in this study. All subjects had normal binocular vision assessed through the Randot Stereopsis test. Subjects also had a near point of convergence (NPC) of less than 6 cm which is described in detail in our previous publication [5]. All subjects signed written inform consent approved by the New Jersey Institute of Technology Institutional Review Board.

B. Eye Movement Recording:

Eye movements were recorded using an infrared (λ=950 nm) system manufactured by Skalar Iris (model 6500, Netherlands). All of the eye movements were within the linear range of the system (±25°). Visual stimuli were displayed

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using a haploscope. Accommodation was held constant at 40 cm from the subject where accommodative vergence has been shown not to influence the initial peak velocity within a disparity vergence response [6].

Two computer screens were used to generate a symmetrical disparity vergence stimulus carefully adjusted along the subject's midline. The stimulus, a green vertical line 2 cm in height and 2 mm in width, was presented on a black background. Two partially reflecting mirrors projected the two vertical lines from the computer screens into the subject's line of sight. Prior to the experimental session, the stimuli from the computer screens were adjusted with mirrors to calibrate the visual stimuli with real targets located at measured distances from the subject's midline. An inter-pupillary distance of 6 cm was assumed. During the experiment, only the visual stimulus displayed on the computer screen was seen by the subject. The subject's head was restrained using a custom chin rest to eliminate head movement thus avoiding any vestibular influences.

The left eye and right eye responses were recorded, calibrated, and saved separately for offline data analysis. Digitization of eye movements was performed with a 12-bit digital acquisition (DAQ) hardware card (National Instruments 6024 E series, Austin, TX, USA). The entire system was controlled by a custom LabVIEW™ program (National Instrument, Austin, TX, USA) which generated the visual stimulus and digitized the eye movement signals at 200 Hz.

C. Vergence Peak Velocity Analysis:

Convergence and divergence step responses were calibrated using two points which were the initial and final position of the convergence and divergence step stimuli. This calibration method has been validated in our previous study [7]. The system has a high degree of linearity, within 3% between ± 25 degrees horizontally; hence a two-point calibration is adequate for this present study[8].

A custom MATLAB™ program (Waltham, MA, USA) was used for all data analysis. Left eye and right eye movement data were converted into degrees. Vergence was calculated by subtracting the right eye movement from the left eye movement to yield a net vergence response. Convergence is denoted as positive and divergence is negative. Blinks and saccadic eye movements were easily identified because of their faster dynamic behaviors compared to vergence movements. Responses with blinks at any point during the movement were omitted. However, the percentage of responses with eye blinks was negligible.

Convergence and divergence peak velocity was computed using a two-point central difference algorithm [9]. The two point central difference algorithm inherently filters the data. To ensure that the range used within the algorithm did not influence the peak velocity of convergence and divergence, a very narrow range was utilized of five data points and this range was increased to seven data points where peak velocity did not change. A range of five data points did not introduce artifacts to the peak velocity [6]. Responses were averaged by aligning the peak velocity of each movement and performing an ensemble average of the responses. This technique was chosen so that the eye movement position and velocity trace could be plotted to show a single subject's behavior without reducing the dynamics especially the peak velocity of the responses [10].

D. Saccade in Vergence Analysis

Saccades were identified using a custom MATLAB™ program (Waltham, MA, USA) [11, 12]. A saccade was identified by averaging both the right eye and the left eye movement. During a pure vergence response, the version saccade response should be approximately zero. However, saccadic responses are commonly observed and easily identified since the peak velocity of saccades (conjugate or disconjugate) are an order of magnitude greater than vergence. Within this study only conjugate saccades were observed. Any responses with saccades greater than 0.15 degrees of magnitude in the transient part of the response (< 1 sec) were detected and analyzed in this study. Only responses containing blinks were omitted from the analysis.

E. *Experimental Protocol:*

Four types of stimuli were presented, summarized in Table 1. The stimuli were randomly presented where approximately 25 to 30 responses of each type of responses were collected. All initial positions were reported as combined vergence demand. To avoid prediction, the response was presented after a random delay between 0.5 to 2.0 seconds because prediction can increase vergence peak velocity [13].

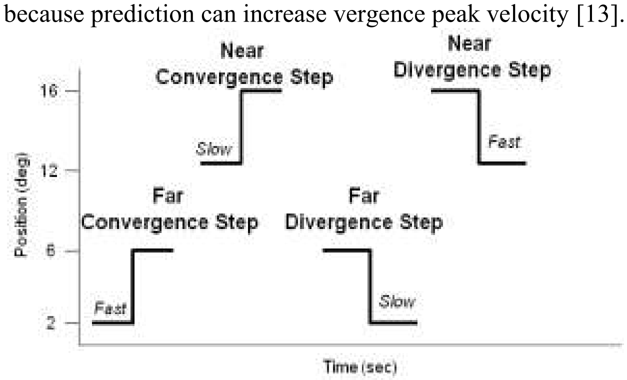

Figure 1. The initial and final position of four vergence stimuli. A previous study by Patel et al. demonstrated that depending upon the initial position of the vergence stimulus, vergence responses will be faster or slower and is labeled accordingly.

RESULTS

Figure 2 plots the average of all individual position and velocity responses aligned using the peak velocity of each response from a symmetrical 4° step stimulus as a function of time for convergence and divergence responses in subject S1 and S2. Subject S3 is not shown in the interest of brevity. The average convergence peak velocity at near is less than the average convergence peak velocity at far. Conversely, the average peak velocity of divergence responses at near is greater than the average divergence peak velocity at far.

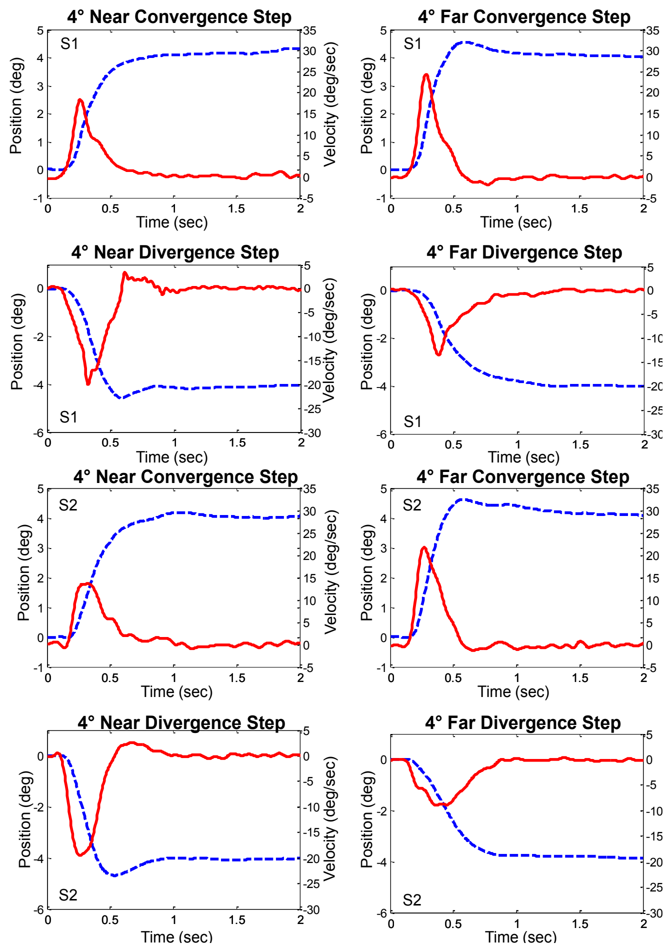

Figure 2: Average of all convergence and divergence position responses (blue solid line) and velocity (red dotted line) responses at near (left column) and far (right column) initial positions from subject 1 and subject 2.

Figure 3 quantifies each subject's average convergence and divergence peak velocity with one standard deviation for the responses located at near and far vergence initial positions.

The summary of the number of saccades per vergence response of all three subjects during the four types of vergence responses are shown in figure 4. All three subjects showed the least amount of saccades during convergence steps at far while all subjects demonstrated the greatest number of saccades during far divergence steps.

The average number of saccades per vergence response is plotted as a function of the average convergence and divergence peak velocity in Figure 5. Using the Pearson's correlation coefficient, the results show that the average number of saccades in vergence responses is highly correlated for convergence ($r = -0.92$) and divergence ($r = -0.70$). The linear fit equations for convergence and divergence steps are: average convergence peak velocity = -9.04 * x + 23.0 and average divergence peak velocity = -5.85 * x + 23.0. Results support that when vergence peak velocity is slower, the number of saccades observed within a vergence movement is increased.

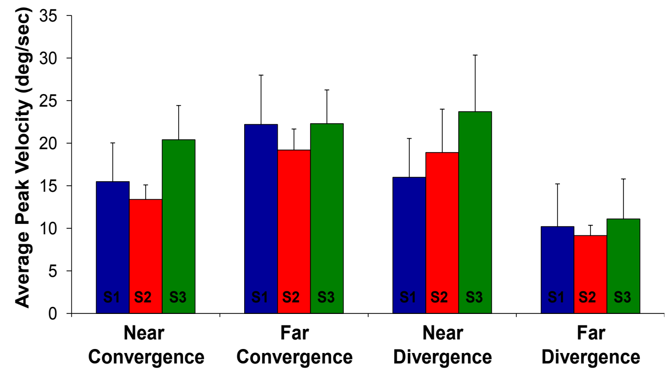

Figure 3: Summary of 4° convergence and divergence steps at near and far initial positions of all three subjects.

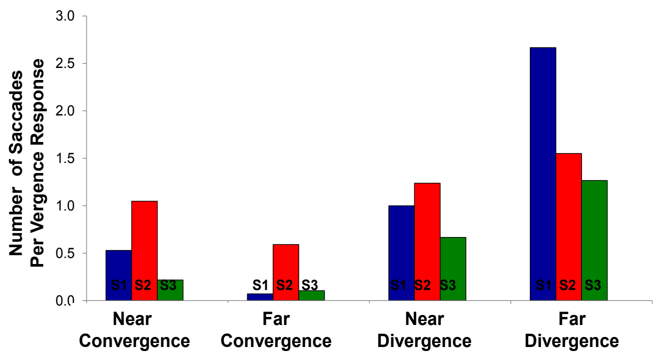

Figure 4: Summary of the average number of saccades per 4° convergence and divergence steps of all three subjects.

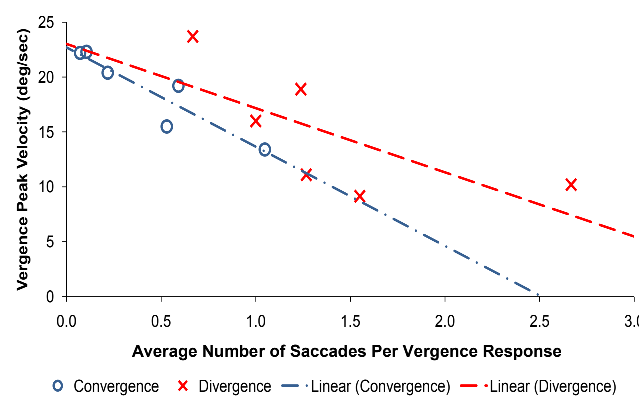

Figure 5: Correlation analysis of the average number of saccades per vergence response versus average convergence (blue circle) and divergence (red cross) peak velocity.

DISCUSSION

Previous studies have shown that saccades increase the speed of vergence responses [1, 12]. However, this is the first study to investigate if the frequency of saccades within a symmetrical vergence movement is correlated to vergence peak velocity.

Zee and colleagues reported that saccades occurred more often during divergence steps compared to convergence steps. Furthermore, when the vergence steps were larger in amplitude, saccades were more frequently observed [1]. Another study also reports that divergence responses contained more saccades than convergence responses [14]. Our preliminary data support this finding. Specifically, the divergence responses with an initial position at far (the slowest movements) had the greatest number of saccades while convergence responses with an initial position at near (the fastest movements) contained the least number of saccades.

The frequency of saccades in vergence is highly correlated to the vergence peak velocity. These data suggest that when the vergence system exhibits slower dynamics, then perhaps the generation of a saccade may be one mechanism to compensate for a slow vergence movement. The recruitment of the saccadic system which has much faster dynamics compared to the vergence system may facilitate the combined eye movement response. We speculate that this strategy is a tradeoff between object recognition and binocular fusion.

In addition, Semmlow and colleagues show the direction of the saccade was consistent within a subject. They speculate this neural strategy may be used by the brain to bring the preferred to dominant eye more quickly to the target for a visual recognition instead of binocular fusion [11].

Future investigations are needed to determine if the dominant eye is correlated to the direction of the saccade within symmetrical vergence responses and whether the amplitude of the saccades is related to the vergence peak velocities.

CONCLUSION

In summary, this study demonstrated that saccades are frequently observed when a person is presented with a pure symmetrical vergence stimulus. Furthermore, the frequency of saccades differs for far and near ranges. Near convergence responses are slower than those located at far and far divergence steps are slower compared to near divergence responses. Prelimiary data suggests that when vergence peak velocity is slower then there is a tendancy to saccade where the frequency of saccades in vergence is highly correlated to the vergence peak velocity.

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