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Quantitative Assessment of Divergence Eye Movements to Ramp Stimuli

Bassem A. Gayed[1], Tara L. Alvarez [1], *Member IEEE*
Department of Biomedical Engineering. New Jersey Institute of Technology, Newark, NJ[1]

Abstract- **Vergence eye movements are the inward (convergence) or outward (divergence) turning of the eyes which allows humans to view images in depth. This study compares converging responses where the stimuli are approaching the subject to diverging responses where the stimuli are moving away from the subject from 10, 6, and 2°/s ramp stimuli. Results show that similar to convergence, divergence may be governed by a two component control system consisting of a transient and sustained component. However, the dynamics of divergence shows a dependency on initial stimulus position which is not apparent for convergent responses. This study also shows that for fast moving divergent responses, high-velocity components were present lending further evidence that a transient component similar in form and function to that found in convergence also exists for divergence. Responses to slow moving responses exhibit smoother tracking where the dynamics of the movement were more uniform throughout the range of the visual field. This implies that the transient component is more prominent in faster responses thus showing a strong dependency on initial stimulus position. With slower moving responses, the transient component did not dominant the movement leading to more homogeneous dynamic responses where a dependency on initial stimulus position was not as apparent.**

I.INTRODUCTION

One of the most sophisticated motor control systems is the oculomotor system. The inward or outward turning of the eyes, vergence, is responsible for binocular vision resulting in visual tracking along the near-far axis in three-dimensional space. The medial and lateral recti muscles rotate the globes horizontally so that paired images are projected to the fovea.

Convergence is the inward turning of the eyes that allows the tracking of a target moving towards a subject. Based on several behavioral and neurophysiology studies, the neural control of convergence is described by the Dual Mode Theory as a two-component system, the transient and sustained components [1], and many behavioral experiments support this control paradigm [1-4]. Perhaps the strongest evidence for dual control is the finding of both smooth and step-like behavior to the same stimulus: a ramp stimulus consisting of a target moving smoothly inward (i.e., convergent) [3]. The transient component is described as being responsible for the system's speed, while the sustained component is modeled with feedback control that determines the system's accuracy. Neurophysiological studies have shown that different cells exist for convergence and for divergence [7]. Thus, divergence is not merely the opposite of convergence, but a distinct subsystem. Although convergence and divergence may have generally similar control properties, and both responses utilize the same extraocular muscles, previous research has shown that the two responses can be different under certain stimulus conditions [5,6]. For instance, in response to step stimulation, divergence responses are dependent on stimulus position while convergent responses are not [8].

This study will present evidence indicating that divergence contains a transient component that augments response velocity. Furthermore, this study will compare ramp responses to several different stimuli ranging from 10°/s to 2°/s and show that faster moving diverging ramps do show a strong correlation to the stimulus initial position whereas slower moving diverging and convergence ramps do not.

II. METHODOLOGY

Four subjects (18 to 63 years old) participated in this study. Two subjects were female (subj:001 and subj:002) and two were male (subj:003 and subj:004). Although age has just recently be indicated to cause a change in the dynamics of vergence movements [9], Rambold and colleagues specify that for convergence age tends to decrease peak velocity. For our study, the oldest subject's dynamics were not less than the younger subjects and thus were included in our analysis. All subjects signed informed consent forms before the experiments that were approved by the New Jersey Institute of Technology (NJIT) Institutional Review Board (IRB).

Disparity vergence stimuli were presented using a dynamic haploscope. Two computer monitors were used to produce a symmetrical disparity vergence stimulus of paired vertical lines. Two partially reflecting mirrors were placed in front of the subject's midline and projected the two stereoscopically paired vertical lines from the stimulus displays into the subject's line of sight.

During an experimental session, different ramp stimuli were presented; 10, 6, 4, and 2°/s ramp stimuli for divergence and 10, 6 and 2°/s ramp stimuli for convergence. Experimental trials began with a randomized stimulus onset delay of 0.5 to 2.0 seconds to avoid subject prediction which might alter vergence dynamics [10]. Divergent and convergent ramps experiments were performed in different sessions.

Eye movements were recorded using an infrared limbus tracking system (wavelength = 950 nm) manufactured by Skalar Iris (model 6500). The presentation of stimuli, signal digitization, and data storage were controlled by a custom LabVIEW (National Instruments, Austin, TX) program. Data acquisition was done at a sampling rate of 200 Hz,

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which is well above the Nyquist frequency for vergence eye movements.

Calibration of leftward and rightward eye-movement responses was performed by recording the output of the eye movement monitor at two known positions before and after each response. Calibration data for each eye were stored with the response and used to construct the eye movement response during offline data analysis.

Data analysis began by converting raw digitized left- and right- eye responses to degrees using the calibration data. The left and right eye responses were subtracted to yield the net disparity vergence movement. When displayed graphically, convergence was plotted as positive, and divergence was plotted as negative. The velocity response was computed using a two-point central difference algorithm[12].

Both convergence and divergence responses to 6°/s ramp stimuli exhibited step-like behavior. This behavior was analyzed by measuring the magnitude of the peak velocity. A single ramp stimulus typically yielded four step-like responses. Data were compared using a within subject 2 x 3 ANOVA where target direction (convergence or divergence) and high-velocity movement (first, second and third since a fourth high-velocity movement was not always observed) were analyzed. For one subject, a fourth high-velocity movement was not observed in 6°/s divergent ramp responses. Specific condition comparisons were evaluated with Bonferroni All-Pairwise Multiple Comparison Tests ($p < 0.05$).

Ramp responses to different ramp stimuli of 10, 6, 4, and 2°/s were also quantified by measuring the magnitude of the high-velocity movements for the first four high-velocity components. Comparisons were made between fast and slow divergence ramp responses. Data were quantified using a custom MATLAB program (Waltham, MA), statistical calculations were performed using NCS2000 (Kaysville, UT) and results were plotted using the software package Axum (Cambridge, MA).

III. RESULTS

Typical divergent (upper plots) and convergent (lower plots) movements from two subjects are shown in Figure 1. For 6°/s divergent and convergent ramp stimuli, high-velocity step-like behaviors can be seen. Despite the smooth nature of the stimulus, smooth tracking is not evident; note particularly the velocity traces in Figure 1.

The convergent responses confirm previous reports that ramp responses to stimuli faster than 2.7°/s generate multiple step-like components [3]. For divergence responses, the magnitude of the peak velocity of the step-like behavior decreases as the stimulus moves away from the subject. However, for convergence, the magnitude of the high-velocity step-like responses does not change significantly as a function of stimulus position. Typically, four step-like responses were observed in all our subjects given the stimulus range of 2° to 20° (18° for one subject) and the stimulus velocity of 6°/s. This was true for both convergence and divergence responses. The associated Bonferroni post-hoc test found that first divergent step-like response differed from the third divergence step-like response. The magnitude of peak velocity decreased between 8% and 56% for subsequent divergence step-like responses. The decrease between the first and third step-like response was on average 34% for the four subjects. For convergence, no trend was evident between the magnitude of the peak velocity and stimulus position for 6°/s ramps.

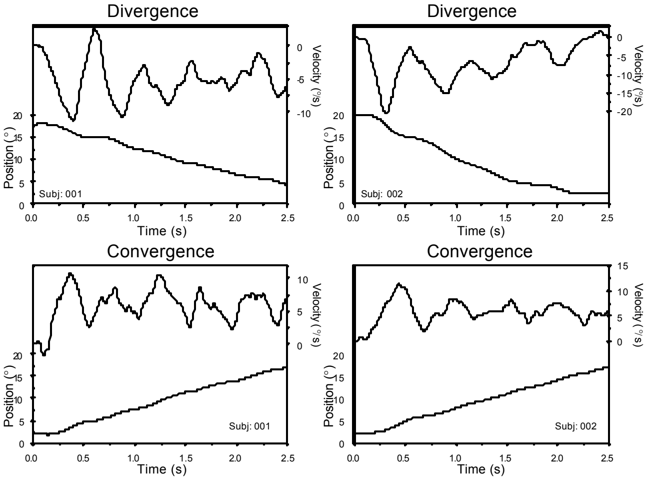

Figure 1: Typical divergence (upper plots) and convergence (lower plots) eye movement recordings stimulated by 6°/s ramp stimuli from two subjects. The position scales are the same but the velocity scales differ. Note, the magnitude of the step-like components seen in divergence decreases as the stimulus moves away from the subject which is not observed for the convergence movements.

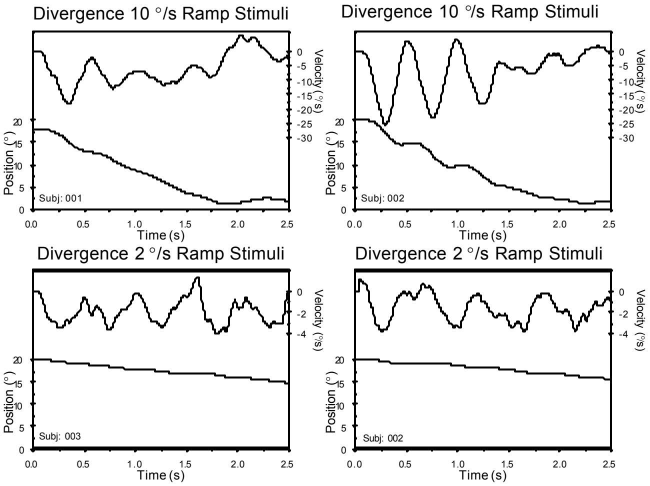

Figure 2: Divergence responses for 10°/s ramp stimuli (upper plots) and 2°/s ramp stimuli (lower plots). The stimulus saturates at a vergence fixation of 2 ° for the faster stimuli. The position traces are the same in all four plots whereas the velocity scale is consistent for the faster responses and the slower responses but not all four plots. For the faster ramp responses, the magnitude of the high-velocity movements decreases as the stimulus moves away from the subject. For the slower moving responses, tracking is smoother compared to the faster responses and the magnitude of the velocity trace does not change as a function of stimulus position.

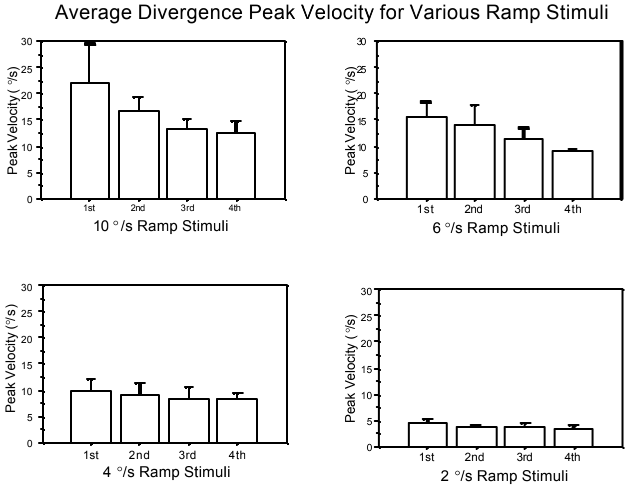

Figure 3: The average magnitude ± standard deviation of the peak velocity for the first four high-velocity movements from four subjects to various ramp stimuli. The upper left plot is from 10 followed by plots for 6, 4, and 2°/s divergent ramp stimuli. The scale for peak velocity is the same for each plot. For the faster moving responses, the magnitude of the step-like movements decreased as the stimulus moved away from the subject. For the slower moving responses the change in peak velocity was not as apparent compared to the faster moving responses. The saturation point for the faster moving responses was a 2° vergence fixation.

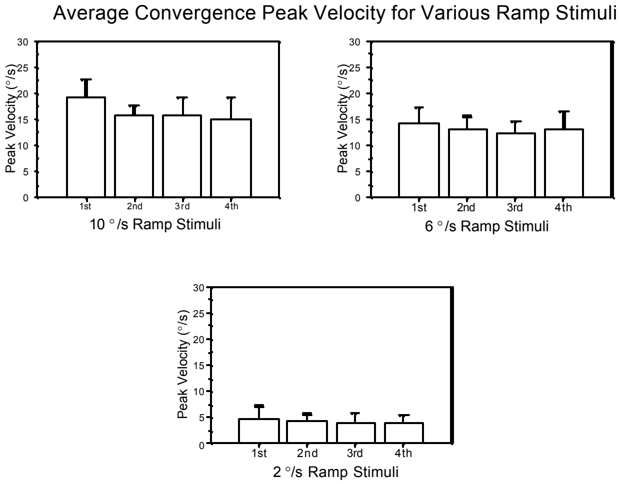

Figure 4: The average magnitude ± standard deviation of the peak velocity for the first four high-velocity movements from four subjects to various convergence ramp stimuli. The upper left plot is from 10 followed by plots for 6, and 2°/s ramp stimuli. The saturation point for faster moving ramps is 2°. The scale for peak velocity is the same for each plot. Note, the dependency on initial stimulus position is not apparent for convergent responses

Divergent responses for ramp stimuli ranging between 10°/s and 2°/s were also investigated. Typical divergence responses to 10°/s (upper plots) and 2°/s (lower plots) ramp stimuli are presented in Figure 2. The faster ramp responses clearly exhibit high-velocity step-like behavior where the magnitude of the high-velocity movements decreases as the stimulus moves away from the subject. The slower ramp responses do not show as distinct high-velocity movements but are smoother tracking. The velocity traces do show some peaks; however, the magnitude of the peaks are relatively equal, not displaying a strong correlation with initial stimulus position as the faster responses did. On average, the first high-velocity movement generated from the 10°/s ramp stimulus decreased 43% compared to the fourth high-velocity movement during divergence, Figure 3. For the responses to 2°/s ramp stimuli, the decrease between the first and fourth high-velocity movement was on average 22% where the variation between the second through fourth was a mere 5%. Average data from the four subjects are quantified in Figure 3 for responses to 10, 6, 4, and 2°/s divergent ramp stimuli. All axes are the same for the four plots. The magnitude of the velocity decreases as the stimulus speed decreases as expected; however the strong correlation between the magnitude of the peak velocity for each high-velocity movement and initial stimulus position also diminishes with the slower ramps. For convergence ramps, Figure 4, a dependency on initial position was not observed.

IV. DISCUSSION

Divergence eye movements have not received the same attention as convergence movements. Neurophysiology research shows that different cells mediate convergent and divergent movements and more cells have been documented for convergence compared to divergence [8,13]. Thus, the control strategy of divergence may be different from convergence and should be analyzed with this in mind. Horng reports that divergence is mediated primarily by the slow control mechanism called the sustained component. He speculated that a transient component may be present, but that it is substantially smaller than the analogous component found in convergence [13].

In a previous study, Semmlow and colleagues used a variety of ramp stimulus velocities (0.7°/s to 36°/s) and these produced a range of ramp-step response amplitudes. From this range of ramp-step amplitudes, they were able to plot the ramp-step responses as a main sequence plot [3]. The main sequence is a plot of peak velocity versus response amplitude and is used to describe relative response velocity. It is commonly used to quantify response dynamics in eye movement research [14]. Semmlow and colleagues determined that although standard step responses had greater peak velocities than ramp-steps of the same apparent movement amplitude, the ramp-step responses showed strong correlation with the standard step main sequence. From this, they concluded that the ramp-step responses were generated utilizing a similar dual-component control scheme as used to produce the standard step response. Our results confirm this finding and also show that divergence also exhibits step-like high-velocity behavior. Thus, divergence and convergence, although quantitatively different, show a general similarity in their control paradigm. This concept is also supported by the neurophysiologic data showing that for divergent movements, both burst and burst-tonic cells were observed indicating that two neural mechanisms are active in divergence control.

One strong difference between the convergence and divergence responses was divergence responses are dependent on stimulus position, at least for the faster responses from 10 and 6°/s ramp stimuli. As the stimulus moved away from the subject, the dynamics of the step-like responses decreased. The position dependency observed in divergence could be attributed to nonlinearities in the extraocular muscles. The arc of muscle contact varies depending on the amount of convergence of the axis of the orbit [15]. However, it is unclear why we would not see such a relationship in convergence eye movements since this mechanism would apply to both converging and diverging movements.

It is also possible that the controller is responsible for the difference observed between the systems. Since different cells exist for convergence and divergence, the control properties could differ. The cause of this difference between convergence and divergence dynamic behavior awaits further investigation.

This study is the first to report a dynamic assessment of divergence ramps to multiple ramp speeds compared to convergence ramps. The faster ramps clearly show a strong correlation to initial stimulus position whereas the slower moving ramp responses exhibited much smoother tracking. The velocity traces for the slower ramp responses where on average a consistent magnitude with a slightly larger initial movement. For the 2°/s ramp responses the magnitude of the velocity components for the second through fourth component only varied on average 5%. Our laboratory has recently published that the transient component as revealed through an independent component analysis decreases as a function of initial position for divergence step responses [16]. These results support the claim that the transient component is more prominent in faster moving ramps thus the magnitude of the high-velocity components decreases as a function of initial position. The slower moving ramps probably do not need as large of a transient component because there is less error introduced to the disparity system; thus, the velocity traces do not show as strong a correlation with initial stimulus position.

V. CONCLUSION

Responses to converging and divergence ramp stimuli exhibited step-like high-velocity movements. This finding confirms research previously reported for convergence and shows that this behavior is common to divergence as well. This finding implies that, as with convergence, divergence may also utilize a control scheme composed of a transient and a sustained component. For divergence, the magnitude of the response peak velocity from faster moving stimuli for each high-velocity component decreased as the target moved away from the subject; but no such trend was observed from convergence. This research shows that the dynamics of divergence responses to ramp stimuli are dependent on stimulus position and presents new evidence that divergence contains a transient component. The dynamics of the slower moving ramps did not show a strong dynamic correlation with initial position implying that the transient component is not as prominent in these responses.

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