Dynamic assessment of disparity vergence ramps

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Received 20 July 2005; accepted 31 March 2006

Abstract

Previous work has shown that the disparity vergence eye movement system responds to inward (i.e., convergent) ramp stimuli with both smooth and step-like behavior depending on target velocity. The responses to diverging ramp stimuli have not been previously studied, but convergence and divergence responses to other stimuli often show different behaviors. Converging and diverging 6°/s ramps were presented to four subjects over a stimulus range of 2°–20°. Step-like behavior was seen in both convergence and divergence responses, but the dynamics was different. For divergent ramps, the peak velocity of each step-like movement decreased as the stimulus moved away from the subject, but no such trend was observed for convergence. The step-like behavior seen in divergence supports the hypothesis that the transient component is active in disparity divergence similar to the transient component proposed for convergent movements. However, the transient component in divergence may be dependent on stimulus position which is not the case for convergence.

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Keywords: Disparity vergence; Oculomotor control; Convergence; Divergence; Eye movements; Vergence dynamics

1. Introduction

Viewing objects in depth is supported by the vergence eye movement system which controls the inward (convergence) and outward (divergence) turning of the eyes. The medial and lateral recti muscles rotate the globes horizontally so that paired images are projected to the fovea. Of the four stimulus inputs that mediate vergence: disparity, accommodation, proximal and tonic, disparity provides the primary drive at least during the dynamic response. This study investigates the dynamics of disparity vergence responses to ramp stimuli.

Convergence is thought to be composed of two underlying control components: a transient component that increases the speed of the movement and a sustained component that produces the highly accurate final position. This two component control structure has been described by the Dual-Mode Theory [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]. In responses to ramp stimuli ranging from 0.7°/s to 36°/s, step-like behavior was observed for faster ramp responses while smooth tracking was elicited for slower moving ramps [3]. The dynamics of the step-like responses generated by the ramp stimuli were similar to normal step responses implying a transient component that behaves similarly in both responses.

The control properties of divergence are not as well understood. This study will present evidence indicating that divergence contains a transient component that augments response velocity. This component is qualitatively similar in form and function to the transient component active in convergence.

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 [7]. Neurophysiologists have also found...
different cells for convergence and divergence indicating that divergence is not merely negative convergence [8]. Here we report the first quantitative assessment of divergence ramp responses. These responses will also be compared to corresponding convergence ramp responses in the same subjects.

2. Methods

2.1. Subjects

Four subjects (18–63-years-old) participated in this study. Two subjects were female (subjects 001 and 002) and two were male (subjects 003 and 004). Although age has just recently been 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). During the experiment, the subject’s head was immobilized using a custom chin rest to avoid any influence from the vestibular system. Subjects were instructed to follow the stimulus target and initiated each experimental trial by depressing a button. All were able to perform the task with ease. One subject was aware of the goals of this study and has been participating in eye movement experiments for many years (subject 004). The other three subjects were naïve to the goals of the study and were inexperienced subjects.

2.2. Experimental design

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. The stimulus displays were calibrated with real targets (as seen through the partially reflecting mirrors) corresponding to 10° and 4° fixation points. During the experiment, only the targets produced by the stimulus display were seen by the subject. Due to the haploscopic viewing conditions, stimuli appeared at the same distance from the subject and accommodation as well as proximal cues associated with depth information were held constant. However, since pinhole viewing was not used, the accommodation system was not open-loop. The stimulus displays were placed 56 cm away from the subject. The targets were a vertical line 3 cm × 2 mm and remained constant throughout the experiment.

During an experimental session, 6°/s ramp stimuli were presented intermixed with 10°/s ramp stimuli. For convergent ramps, the stimulus began at a 2° fixation point and ended at a 20° fixation point for subjects 002, 003 and 004. Divergence ramps began at the near point and ended at 2°. For subject 001, the near point was 18° as this was the maximum comfortable convergence for this subject. Experimental trials lasted for 3.5 s with a randomized stimulus onset delay of 0.5–2.0 s to avoid subject prediction which might alter vergence dynamics [10]. Divergent and convergent ramps experiments were performed in different sessions. The ramp stimuli were randomly presented with other ramps of different speeds. Thus, the stimulus onset and speed were randomized to reduce the influence of prediction.

Eye movements were recorded using an infrared limbus tracking system (λ = 950 nm) manufactured by Skalar Iris (model 6500). All eye movements were well within the system’s ±25° linear range assuming proper set up. The left and right eye movements were recorded and saved separately. The presentation of stimuli, signal digitization, and data storage were controlled by a custom LabVIEW program. Data acquisition was done at a sampling rate of 200 Hz, which is well above the Nyquist frequency for vergence eye movements.

Calibration of left and right 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. Using the same instrumentation, a study comparing two versus three calibration points showed that the average working nonlinearity was 3% of the total movement amplitude with a maximum nonlinearity of 5% [11]. Since the nonlinearities of our system were small, we used two calibration points to convert the data to degrees.

2.3. Data analysis

Data analysis began by converting raw digitized left and right responses to degrees using the calibration data. The left and right eye movements were inspected individually and responses that contained blinks or saccades during the transient portion of the response were omitted from analysis. Saccades were easily identified based upon their fast dynamic properties. 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 and the corresponding response amplitude when peak velocity occurred. These parameters are most easily measured by plotting responses in the phase domain, a plot of velocity as a function of response amplitude (Figs. 1 and 2 right plots). A single ramp stimulus typically yielded four step-like responses. Data were compared using a within subject 2 × 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 divergent ramp responses. Specific condition comparisons were evaluated
with Bonferroni All-Pairwise Multiple Comparison Tests ($p < 0.05$). 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).

3. Results

Typical divergent and convergent movements from two subjects are shown in Figs. 1 and 2, respectively. The left-hand plots display the position and velocity of the eye movements as a function of time. For $6^\circ$/s convergent and divergent 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 Figs. 1 and 2. The convergent responses confirm previous reports that ramp responses to stimuli faster than $2.7^\circ$/s generate multiple step-like components [3]. The step-like behavior seen in divergence has not been previously reported. Figs. 1 and 2 also show the responses as a phase plot which is a plot of the responses’ velocity as a function of its position. 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.

These observations were quantified by measuring the magnitude of peak velocity for each step-like component and the corresponding amplitude of the response when the peak velocity occurred, Table 1. Typically, four step-like responses were observed in all our subjects given the stimulus range of $2^\circ$–$20^\circ$ (18$^\circ$ for one subject) and the stimulus velocity of $6^\circ$/s. This was true for both convergence and divergence responses. For divergent movements, the magnitude of peak velocity decreased as a function of response amplitude, Table 1 and Fig. 3. The statistical analysis revealed a statistically significant $F(2, 6) = 17.1, p < 0.005$. 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.

Summary plots of the magnitude of peak velocity including standard deviation can be seen in Figs. 3 and 4 for

![Time Domain](image1.png)

![Phase Domain](image2.png)

**Fig. 1.** Typical divergence eye movement recordings from two subjects. The left side shows the time domain plot of position (solid lower traces) and velocity (solid upper traces). Note, the magnitude of the step-like components seen in divergence decreases as the stimulus moves away from the subject. The right side shows the phase plot of the responses shown on the left. The phase plot is a plot of velocity ($^\circ$/s) as a function of position ($^\circ$) and emphasizes the dynamic features of the response.
The magnitude of the step-like components in convergence does not change significantly as the stimulus moves toward the subject. For responses with fewer step-like components, the number observed is noted. Many responses generated four step-like components. For responses with fewer step-like components, the number observed is noted.

Table 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Divergence</th>
<th>Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vel (°/s)</td>
<td>Amp (°)</td>
</tr>
<tr>
<td>Subj:001</td>
<td>11.3 ± 1.8</td>
<td>16.4 ± 0.55</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 14</td>
<td>N = 14</td>
</tr>
<tr>
<td>1st High Velocity</td>
<td>10.6 ± 1.1</td>
<td>13.5 ± 0.77</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 14</td>
<td>N = 14</td>
</tr>
<tr>
<td>2nd High Velocity</td>
<td>9.23 ± 0.94</td>
<td>10.2 ± 0.72</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 14</td>
<td>N = 14</td>
</tr>
<tr>
<td>3rd High Velocity</td>
<td>8.52 ± 0.86</td>
<td>7.77 ± 0.72</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 14</td>
<td>N = 14</td>
</tr>
<tr>
<td>4th High Velocity</td>
<td>16.6 ± 3.8</td>
<td>2.13 ± 0.51</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 15</td>
<td>N = 15</td>
</tr>
<tr>
<td>2nd High Velocity</td>
<td>14.7 ± 4.5</td>
<td>6.91 ± 2.1</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 15</td>
<td>N = 15</td>
</tr>
<tr>
<td>3rd High Velocity</td>
<td>14.9 ± 6.4</td>
<td>11.0 ± 2.0</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 13</td>
<td>N = 13</td>
</tr>
<tr>
<td>4th High Velocity</td>
<td>13.9 ± 4.8</td>
<td>14.4 ± 1.0</td>
</tr>
<tr>
<td>Movement</td>
<td>N = 6</td>
<td>N = 6</td>
</tr>
</tbody>
</table>

Peak velocity (± standard deviation) along with the corresponding amplitude when a given peak velocity occurred (± standard deviation). Values are given for each step-like component in the response. The number of samples is included. Many responses generated four step-like components. For responses with fewer step-like components, the number observed is noted.
4. 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 [14].

In a previous study, Semmlow and colleagues used a variety of ramp stimulus velocities (0.7°/s–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 [15]. 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. Current experiments are being conducted to determine if the dynamic similarities between standard steps and ramp steps also holds for divergence.

One strong difference between the convergence and divergence responses was divergence responses are dependent on stimulus position. As the stimulus moved away from the subject, the dynamics of the step-like responses decreased. Subjects were placed in the dark to diminish proximal cues and only viewed the stimulus targets through the haploscope. It was unlikely that the subjects were aware of the vergence magnitude of the stimulus. However, the neural signals to the final common pathway would be different and the extraocular muscles would experience different forces dependent on the rotational position of the globe. 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 [16]. 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. For divergence, the synchronization of the cells could vary depending on the level of tonic activity: when the stimulus is closer and tonic activity is higher, a greater magnitude of bursting activity may be produced. This is similar to the argument of the pulse-step mismatch observed in glissadic overshoots in saccades [17]. The cause of this difference between convergence and divergence dynamic behavior awaits further investigation.

5. Summary

Responses to converging and divergence ramp stimuli of 6°/s were recorded in four subjects using an infrared eye movement
monitor. Stimuli were presented with a haploscope where accommodation was held constant and proximal cues reduced. Responses exhibited step-like high velocity behavior in both convergence and divergence ramp responses. 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.

Typically four step-like responses were observed over the stimulus range of 2°–20°. For divergence, the magnitude of the response peak velocity for each component decreased as the target moved away from the subject; but no such trend was observed from convergence. The difference in the behavior of convergence and divergence responses could be explained by nonlinearities in the extraocular muscles or in differences in neural command signals. 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.

Acknowledgements

This research was supported by Essilor International and by a Career Award from the National Science Foundation (BES-0537072 and BES-0447713).

References


Tara L. Alvarez received her B.S. in Electrical Engineering from Rutgers University and her M.S. and Ph.D. in Biomedical Engineering also from Rutgers University. From 1998 to 2001, she worked as a Member of the Technical Staff at Bell Laboratories. She joined the Department of Biomedical Engineering at the New Jersey Institute of Technology in 2005 as an Assistant Professor and Director of the Vision and Neural Engineering Laboratory. She won the National Science Foundation (NSF) CAREER award in 2005. She has published over 40 papers in referred journals and conference proceedings and is a member of ARVO and IEEE EMBS. For more information regarding her work, please visit http://web.njit.edu/~alvarez/.

John L. Semmlow was born in Chicago, in 1942, and received the BSEE degree from the University of Illinois in Champaign in 1964. Following several years as a design engineer for Motorola, Inc., he entered the Bioengineering Program at the University of Illinois Medical Center in Chicago, receiving the Ph.D. in 1970. He has held faculty positions at the University of California, Berkeley, and the University of Illinois, Chicago, and currently holds a joint position as Professor of Surgery, UMDNJ-Robert Wood Johnson Medical School and Professor of Biomedical Engineering at Rutgers University, New Jersey. In 1985, he was a NSF/CNRS Fellow in the Sensorimotor Control Laboratory of the University of Provence, Marseille, France. He was appointed a Fellow of the IEEE in 1994 in recognition of his work in acoustic detection of coronary artery disease, a Fellow of AIMBE in 2003, and a Fellow of BMES in 2005. He was founding chair of the International Conference on Vision and Movement in Man and Machines, first held in Berkeley in 1995. His primary research interests include discovering strategies for how the brain controls human motor behavior such as eye movements, the characteristics of the aging eye and lens, the development of improved imaging technologies, particularly in the eye, and medical instrumentation. He is an avid, if somewhat dangerous, skier, an enthusiastic, but mediocre, tennis player, and he enjoys the slow, but nonetheless very expensive, hobby of sailing.

Claude Pedrono received his B.S. in optical engineering from Paris Optics School in 1975. He worked at Essilor Instruments Department from 1977 to 1982. In 1982, he joined the Physiological Optics Laboratory. Currently, he is responsible for the Posture and Vision Exploratory Role in the Essilor Research and Development Department. He holds over 10 patents on ophthalmic lenses and control apparatus.