

# Divergence eye movements are dependent on initial stimulus position

Tara L. Alvarez<sup>a,\*</sup>, John L. Semmlow<sup>b,c</sup>, Claude Pedrono<sup>d</sup>

<sup>a</sup> Department of Biomedical Engineering, New Jersey Institute of Technology, University Heights, Newark, NJ 07102, United States

<sup>b</sup> Department of Biomedical Engineering, Rutgers University, Piscataway, NJ, United States

<sup>c</sup> Department of Surgery, Bioengineering, Robert Wood Johnson Medical School, UMDNJ Piscataway, NJ, United States

<sup>d</sup> Essilor International S.A. Saint Maur, France

Received 30 July 2004; received in revised form 11 January 2005

## Abstract

Previous studies on the speed and latency of convergence and divergence eye movements have produced varied, sometimes contradictory, results. Four subjects were studied and tracked 4° disparity step changes for convergence and divergence at different initial target positions. Here we report that the dynamics of divergence movements not only differ from convergence movement, but depend on the initial vergence position. Velocities of divergence eye movements in response to targets that were initially near to the subject were approximately twice that of responses to initially distant targets and also exhibited shorter temporal properties. Hence, while convergence responses are fairly similar irrespective of the initial position, divergence dynamic and temporal properties are dependent on the initial stimulus position. It is speculated that the differences observed in divergence may be the result of nonlinear properties of the extraocular muscles or a difference in the underlying neural controller potentially a difference in the magnitude of the fusion initiating component of divergence.

© 2005 Elsevier Ltd. All rights reserved.

**Keywords:** Convergence; Divergence; Oculomotor control; Eye movements; Vergence dynamics

## 1. Introduction

The vergence system is responsible for the convergence and divergence movement of the eyes allowing the visual system to fuse stimuli moving in depth. This disjunctive movement of the eyes is facilitated by the medial and lateral recti muscles which rotate the globes, until paired images project onto the foveas.

Controversy exists in the literature related to the dynamic and temporal relationship between convergence and divergence. Several studies report that convergence is faster than divergence (Hung, Ciuffreda, Semmlow, & Horng, 1994; Hung, Semmlow, & Ciuffreda, 1986; Hung, Zhu, & Ciuffreda, 1997; Zee, Fitzgibbon, &

Optican, 1992) by as much as double (Hung et al., 1994), while other studies report pure divergence and convergence to have approximately the same velocity characteristics (Collewyn, Erkelens, & Steinman, 1995). Specifically, while analyzing the main sequence (an indicator of the first order dynamics), one study showed convergence to have a main sequence double that of divergence where the initial stimulus position was 8° (Hung et al., 1994). This investigation will show that the speed of responses and related dynamic properties of divergence vary as a function of initial position. Depending on the initial location of the stimulus, the relationship between convergence and divergence dynamic properties can vary dramatically.

Several studies also report inconsistencies in the temporal relationship between convergence and divergence. Rashbass and Westheimer (1961) state that divergence and convergence have similar latencies (i.e. reaction

\* Corresponding author. Tel.: +1 973 596 5272; fax: +1 973 596 5222.  
E-mail address: [tara.l.alvarez@njit.edu](mailto:tara.l.alvarez@njit.edu) (T.L. Alvarez).

Table 1  
Summary of previous findings for convergence and divergence latency  $\pm$  standard deviation when information was available

Latency (ms)		Study
Convergence	Divergence	
180	190	Semmlow and Wetzel (1979)
161	182	Hung et al. (1997)
250	210	Krishnan et al. (1973)
150 $\pm$ 30	130 $\pm$ 20	Alvarez et al. (2002)
219 $\pm$ 7	198 $\pm$ 8	Yang et al. (2002)

times) of 160–170 m. Other reports state that convergence latency is less than divergence latency (Hung et al., 1997; Semmlow & Wetzel, 1979). Conversely, researchers have published convergence to have a longer latency than divergence (Alvarez, Semmlow, Yuan, & Munoz, 2002; Krishnan, Farazia, & Stark, 1973). Previous findings regarding convergence and divergence are summarized in Table 1. All of these studies had a limited set of subjects. A recent study by Yang, Bucci, and Kapoula (2002) reports that the latency for convergence is greater than divergence for the 15 adult subjects studied, documenting differences that were statistically significant,  $P < 0.01$ .

Latency does vary between individuals, which may account for some of the controversy in the literature; however, the present study shows that for a given subject, convergence does not demonstrate a strong dependency on initial position; whereas, divergence eye movements are dependent on the initial stimulus position. Depending on where the initial targets are located in space influences the latency of divergence; thus, initial target positioning will determine whether the convergence latency is greater or less than divergence latency.

## 2. Methods

### 2.1. Subjects

Four subjects (18–60 years old) participated in this study. Two subjects were male, and two were female. 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 subjects' head were immobilized using a custom chin rest to avoid any influence from the vestibular system. They were instructed to initiate an experiment by depressing a button and to maintain binocular fixation on the stimulus target. All were able to perform the task easily. One subject (Subject 004 who is 60 years old) was aware of the goals of this study and has been participating in eye movement experiments for many years. 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 reflective 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 corresponding to 10° and 4° fixation points. Using the same instrumentation design, a study comparing two versus three calibration points showed that the average nonlinearity was 3% of the total movement with a maximum nonlinearity of 5% (Horng, Semmlow, Hung, & Ciuffreda, 1998a, 1998b). Since the nonlinearities of our system were small, we used two calibration points to convert the data to degrees. Only the targets produced by the stimulus displays were seen by the subject during the experiment, and no proximal cues associated with depth information related to the target distance were present (Rosenfield & Ciuffreda, 1991).

During an experimental session, a variety of convergent or divergent stimuli were presented. All stimuli were 4° step changes in disparity vergence. For the divergence experiments, stimuli began at initial vergence positions of 20°, 16°, 12°, and 8°. One subject, subj001, could not fuse a 20° stimulus, so her initial vergence positions were limited to 18°, 16°, 12°, and 8°. The four stimuli were randomly presented after a random delay of 0.5–2.0 s to avoid subject prediction which can alter vergence dynamics (Yuan, Semmlow, & Munoz, 2000; Alvarez et al., 2002). The convergence experiments also had four initial positions: 16°, 12°, 8° and 4°. The 16° initial position was not included for the one subject (subj001) who could not fuse a 20° near target. Hence the range of all convergent stimuli overlapped the range of divergent stimuli.

Eye movements were recorded using an infrared limbus tracking system ( $\lambda = 950$  nm) manufactured by Skalar Iris (model 6500). The manufacturer reports a resolution of 2 min of arc. All eye movements were well within the system's  $\pm 25^\circ$  linear range assuming proper set-up. The left and right eye movements were recorded and saved separately. The presentation of stimuli and the digitization of signals that were saved to disk 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.

### 2.3. Data analysis

Data analysis began by converting raw digitized left and right responses to degrees using the calibration data. Some investigations have shown that saccades alter vergence responses (Collewijn et al., 1995; Zee et al., 1992). While another study believes the alternation in saccade–vergence trajectories is due to the difference of free and instrument viewing environments (Hung, 1998). To avoid controversy, 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 faster dynamic properties compared to vergence. The main objective of this analysis was to investigate the dynamic change in the responses, so movements that contained small saccades during the final, steady-state portion were analyzed as long as the saccades in the

two eyes cancelled in the net vergence response. 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 (Bahill, Kallman, & Lieberman, 1982).

Data were analyzed by measuring the magnitude of the peak velocity, latency and the time to maximum velocity. The latency was measured as the difference between stimulus and movement onset which is an index used by other researchers (Alvarez et al., 2002; Krishnan et al., 1973). Time to maximum velocity was also measured from stimulus onset. Individual subject data were compared using an unpaired student *t*-test to determine if the dynamic changes were statistically significant. Data were analyzed using MATLAB (Waltham, MA) and were plotted and statistically analyzed using the software package Axum (Cambridge, MA).

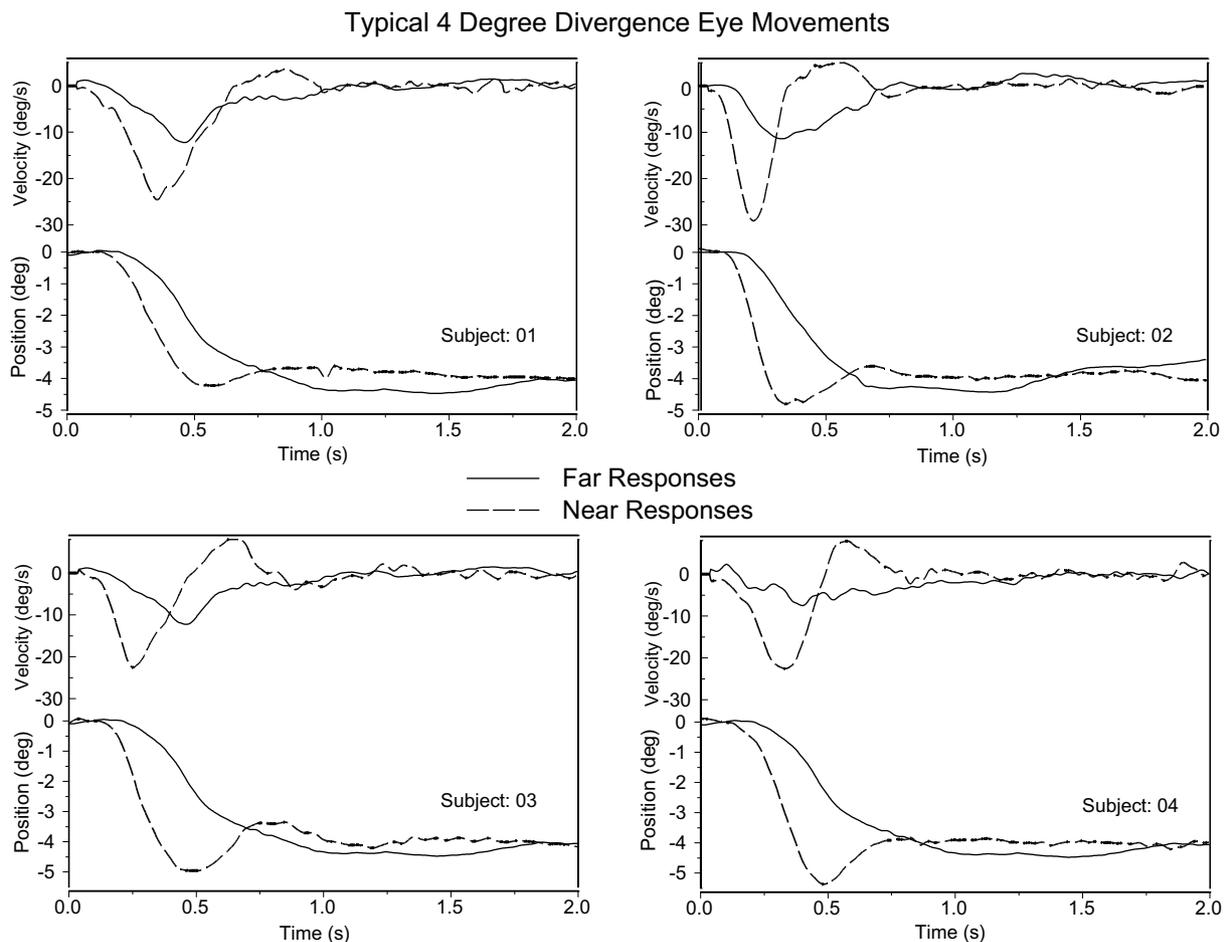


Fig. 1. Typical divergence movements to 4° step changes in disparity vergence for each subject. Lower traces are position (°) and upper traces are velocity (°/s). The dashed lines represent responses to stimuli that began closer to the subject, 18° for subject 01 and 20° for subjects 02, 03, and 04. The responses that began with the far stimuli (8° for all subjects) are shown as with solid lines. Qualitatively, the near and far responses exhibit different temporal and dynamic characteristics dependent on the initial position for all four subjects studied.

### 3. Results

Typical individual divergence eye movements are shown for each subject in Fig. 1. The upper traces are velocity and the lower traces are vergence position. The near and far responses exhibit clear differences. The dashed line shows responses that began near to the subject,  $20^\circ$  for subjects 002 through 004 and  $18^\circ$  for subject 001. Qualitatively, the divergence responses to stimuli near to the subject occurred earlier and with a greater peak velocity compared to responses to stimuli far from the subject. Conversely, qualitative inspection of convergence eye movements did not show a consistent change in temporal or dynamic properties when the initial position was randomly varied for all subjects, Fig. 2.

Data were quantified dynamically and temporally by measuring the maximum magnitude of velocity (Table 2), latency (Table 3), and the time to peak velocity (Table 3). All temporal properties were measured from stimulus onset. Combined data from all subjects can

be seen graphically in Fig. 3 for divergence and Fig. 4 for convergence.

For divergence movements to the same  $4^\circ$  step change in disparity, the magnitude of peak velocities for the near responses (initial position of  $20^\circ$  or  $18^\circ$ ) were approximately twice that of the far responses (initial position of  $8^\circ$ ). When comparing the responses to near and far stimuli, the dynamic differences were statistically significant ( $P < 0.0001$ ) for all four subjects individually and combined, see Fig. 3A and Table 4. Conversely, convergence dynamics did not show a consistent trend for the four subjects studied when comparing responses to the near initial position ( $16^\circ$  for subjects 002 through 004 or  $12^\circ$  for subject 001) with the far initial position ( $8^\circ$  for all subjects). Subjects 002 and 003 did show some difference between near and far  $4^\circ$  responses ( $P < 0.01$ ); however when data were combined for all subjects, the  $P$  value was not significant ( $P < 0.2$ ). Fig. 4 presents the combined convergence results and Table 4 presents the statistical information.

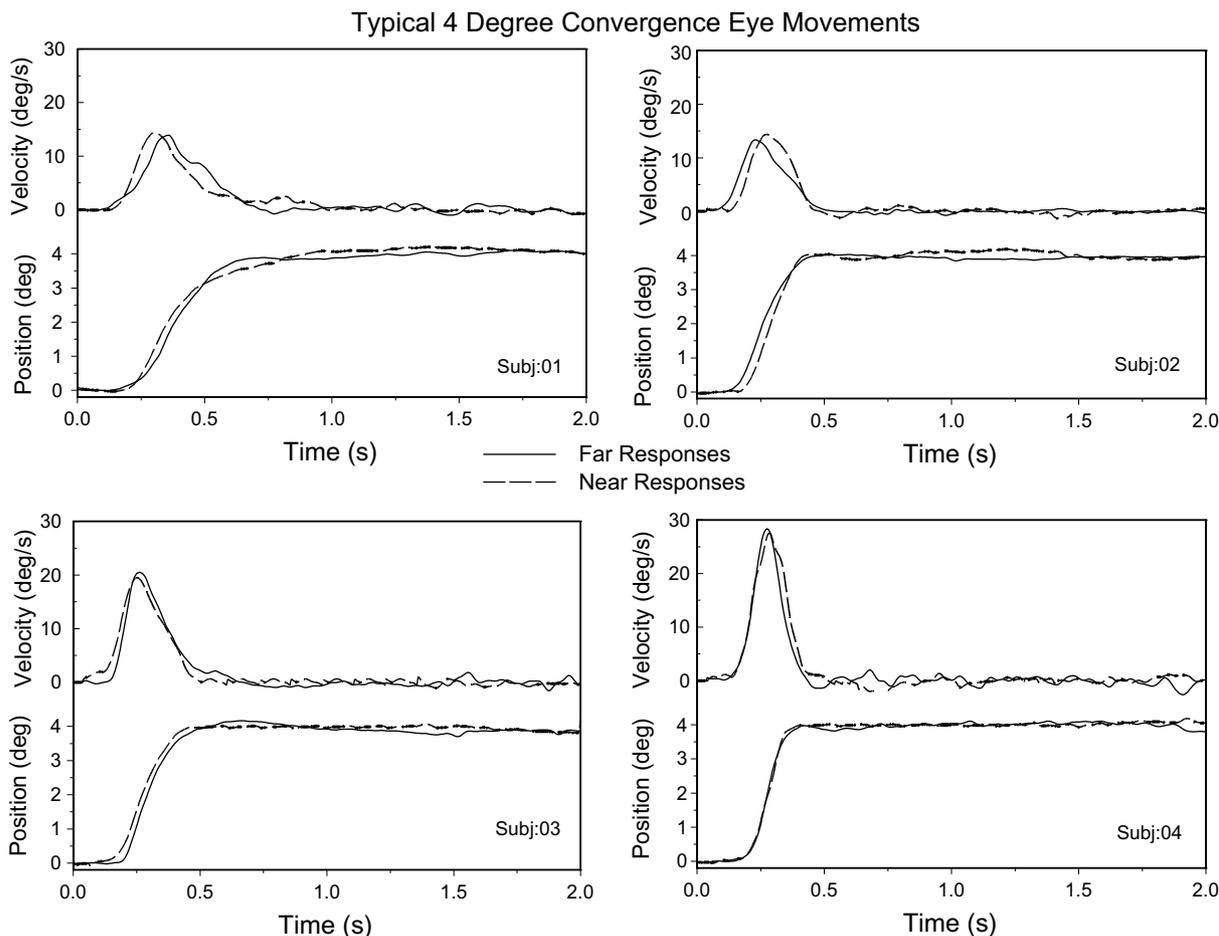


Fig. 2. Typical convergence movements to a  $4^\circ$  step changes in disparity vergence for each subject. Lower traces are position ( $^\circ$ ) and upper traces are velocity ( $^\circ/s$ ). The dashed lines represent responses to stimuli that began closer to the subject,  $14^\circ$  for subject 01 and  $16^\circ$  for subjects 02, 03, and 04. The responses that began with the far stimuli ( $4^\circ$  for all subjects) are shown as with solid lines. Qualitatively, the near and far responses do not show different temporal and dynamic characteristics for the near and far stimuli for all four subjects studied.

Table 2  
Dynamic study of divergence and convergence movements for responses to stimuli of varying initial positions

Stimulus (°)	Velocity (°/s) ± Standard deviation			
	Subject: 001	Subject: 002	Subject: 003	Subject: 004
<i>Divergence</i>				
20–16	17.56 ± 3.14 <sup>a</sup> N = 19	20.47 ± 5.49 N = 18	19.35 ± 4.60 N = 11	21.10 ± 4.83 N = 29
16–12	14.51 ± 2.80 N = 18	18.16 ± 5.86 N = 19	18.58 ± 5.95 N = 20	16.29 ± 2.71 N = 36
12–8	12.47 ± 3.95 N = 17	12.12 ± 2.00 N = 13	12.05 ± 2.66 N = 11	11.57 ± 2.54 N = 21
8–4	12.17 ± 1.35 N = 10	10.34 ± 2.31 N = 25	8.08 ± 1.37 N = 19	11.29 ± 2.37 N = 50
<i>Convergence</i>				
16–20	Not enough Data	7.53 ± 1.21 N = 18	18.07 ± 4.88 N = 38	31.19 ± 6.47 N = 22
12–16	9.13 ± 3.60 N = 13	11.27 ± 2.39 N = 40	18.32 ± 4.71 N = 35	31.40 ± 5.08 N = 24
8–12	9.79 ± 3.39 N = 35	12.57 ± 3.18 N = 14	18.53 ± 4.98 N = 31	33.64 ± 4.26 N = 20
4–8	11.36 ± 3.87 N = 50	11.78 ± 2.01 N = 16	20.82 ± 3.82 N = 35	34.76 ± 6.14 N = 14

<sup>a</sup> Subject 001 could not fuse 20°. These responses are from 18° to 14° stimuli.

The latency and time to maximum velocity were also measured, Table 3. For divergence movements, the latency increased as the stimulus moved further from the subject. In Fig. 1, the far responses (solid lines) occur later than the near responses (dashed lines). The difference in latency between the near and far responses was as large as 56 ms and three of the four subjects showed individual differences of statistical significance ( $P < 0.0232$ ), Fig. 3B and Table 4. Conversely, convergence movements did not show a statistically significant difference in latency when comparing near and far responses ( $P > 0.2$ ), Table 4.

Other divergence response characteristics decreased when comparing near and far initial starting positions. The time to peak velocity was delayed as the stimulus moved further from the subject with a maximum difference of 215 ms. Statistical significance was observed in three of the four subjects ( $P < 0.004$ ). The value of this variable as a function of initial position is given for all four subjects in Fig. 3C and Table 4. For convergence movements, the time to maximum velocity did not show consistent trends when comparing the near and far responses for all subjects, Fig. 4C and Table 4.

An additional experiment was performed using 8° step changes in disparity vergence. The initial stimulus positions were 20°, 16°, 12° and 8°. Only subject 004 participated in this experiment, since only this subject could produce saccade free 8° vergence eye movements for this range of initial positions. A typical near (20° initial target position) and far (8° initial target position) response is shown in Fig. 5. Similar to the 4° responses, the 8° responses had significantly faster dynamics ( $P < 0.0001$ ;  $t = 4.6066$ ;  $df = 27$ ) and shorter latency

properties ( $P = 0.0003$ ;  $t = 4.1599$ ;  $df = 27$ ) for near responses compared to responses to stimuli further from the subject, Table 5. This result suggests that the dependency of vergence dynamics on stimulus initial position generalizes to larger responses.

## 4. Discussion

### 4.1. Comparison of convergence and divergence

When reviewing the dynamics of convergence and divergence, the relationship was dependent on the initial positional conditions. For example, looking at subject 003's data, convergence and divergence had relatively similar peak velocities when responses were recorded close to the subject between 16° and 20° ( $19.36 \pm 4.60^\circ/\text{s}$  for divergence and  $18.07 \pm 4.88^\circ/\text{s}$  for convergence). This is similar to the findings of Collewijn et al. (1995) who do not report the initial starting position of their stimuli. However, when the responses were obtained at a stimulus range of 4–8°, the relationship between dynamics changed where convergence was approximately twice as fast as divergence ( $8.08 \pm 1.37^\circ/\text{s}$  for divergence and  $20.82 \pm 3.82^\circ/\text{s}$  for convergence). This finding is the same as that reported by Hung et al. (1997) who also report their responses were recorded at an initial starting position of 8°. Since the divergence system is dependent on the initial position of the stimulus, any comparison between convergence and divergence must take into account the stimulus range.

When comparing divergence and convergence responses to the same 4° step change in disparity, the

Table 3

Temporal analysis of divergence and convergence movements quantifying the latency, time constant and time to maximum velocity ( $V_{max}$ ) with the standard deviation (STD) and the number of samples ( $N$ )

Subject	Stimulus	$N$	Latency (ms) $\pm$ STD	Time to $V_{max}$ (ms) $\pm$ STD
<i>Divergence</i>				
001	18–14	19	166 $\pm$ 49	354 $\pm$ 66
	16–12	18	179 $\pm$ 40	354 $\pm$ 63
	12–8	17	176 $\pm$ 46	351 $\pm$ 66
	8–4	10	185 $\pm$ 42	388 $\pm$ 27
002	20–16	18	111 $\pm$ 12	147 $\pm$ 18
	16–12	19	126 $\pm$ 32	174 $\pm$ 21
	12–8	13	109 $\pm$ 14	171 $\pm$ 24
	8–4	25	123 $\pm$ 19	171 $\pm$ 30
003	20–16	11	131 $\pm$ 27	294 $\pm$ 44
	16–12	20	139 $\pm$ 35	305 $\pm$ 51
	12–8	11	160 $\pm$ 38	359 $\pm$ 87
	8–4	19	187 $\pm$ 27	397 $\pm$ 96
004	20–16	29	113 $\pm$ 20	287 $\pm$ 43
	16–12	36	124 $\pm$ 22	317 $\pm$ 51
	12–8	21	144 $\pm$ 42	361 $\pm$ 65
	8–4	50	152 $\pm$ 43	502 $\pm$ 74
<i>Convergence</i>				
001	12–16	13	190 $\pm$ 27	396 $\pm$ 87
	8–12	35	220 $\pm$ 81	434 $\pm$ 85
	4–8	50	198 $\pm$ 51	449 $\pm$ 62
002	16–20	18	154 $\pm$ 16	324 $\pm$ 45
	12–16	40	161 $\pm$ 31	345 $\pm$ 48
	8–12	14	154 $\pm$ 21	293 $\pm$ 32
	4–8	16	156 $\pm$ 19	303 $\pm$ 24
003	16–20	38	171 $\pm$ 27	293 $\pm$ 47
	12–16	35	156 $\pm$ 36	275 $\pm$ 32
	8–12	31	166 $\pm$ 27	270 $\pm$ 33
	4–8	35	162 $\pm$ 27	291 $\pm$ 30
004	16–20	22	190 $\pm$ 38	303 $\pm$ 31
	12–16	24	174 $\pm$ 30	294 $\pm$ 26
	8–12	20	174 $\pm$ 34	298 $\pm$ 23
	4–8	14	178 $\pm$ 23	306 $\pm$ 23

relationship of latency was also dependent on where the stimulus was located. Reviewing subject 003's data for vergence changes between 16° and 20°, the latency was 131  $\pm$  27 ms for divergence and 171  $\pm$  27 ms for convergence–divergence latency being less than convergence. However, for a stimulus range of 4–8° the latency was 187  $\pm$  27 ms for divergence and 162  $\pm$  27 ms for convergence–convergence latency being less than divergence. The difference between near and far responses for convergence latency was not significantly different ( $P = 0.16$ ). However, for the same stimuli range the divergence response latency was significantly different ( $P < 0.0001$ ). Thus, stimulus range strongly influences the relationship between convergence and divergence latency.

#### 4.2. Differences explained by extraocular muscles

The dependence of vergence dynamics on initial position may be a result of nonlinear properties in the ocu-

lomotor muscles. As with any system, it may appear linear over a limited range; however when you study the system over an extended range, nonlinearities may become apparent. One possible explanation for potential nonlinearities could be difference in the arc of contact. The arc of contact is defined as the arc between the tangential point and the center of the insertion of the muscle on the sclera. Based on a mechanical model, Weiss showed that depending on the divergence of the axis of the orbit, a considerable difference in the arc of contact of the medial and lateral rectus muscle is found (Burian & von Noorden, 1985). Another explanation may be the basic physiology of the extraocular muscles. The insertions of the rectus muscles are not equidistant from the corneal limbus, thus they do not form a concentric circle but lie on the spiral of Tillaux. The medial rectus muscle is closer to the corneal limbus compared to the lateral rectus. Furthermore, when comparing the medial and lateral rectus muscles the medial rectus

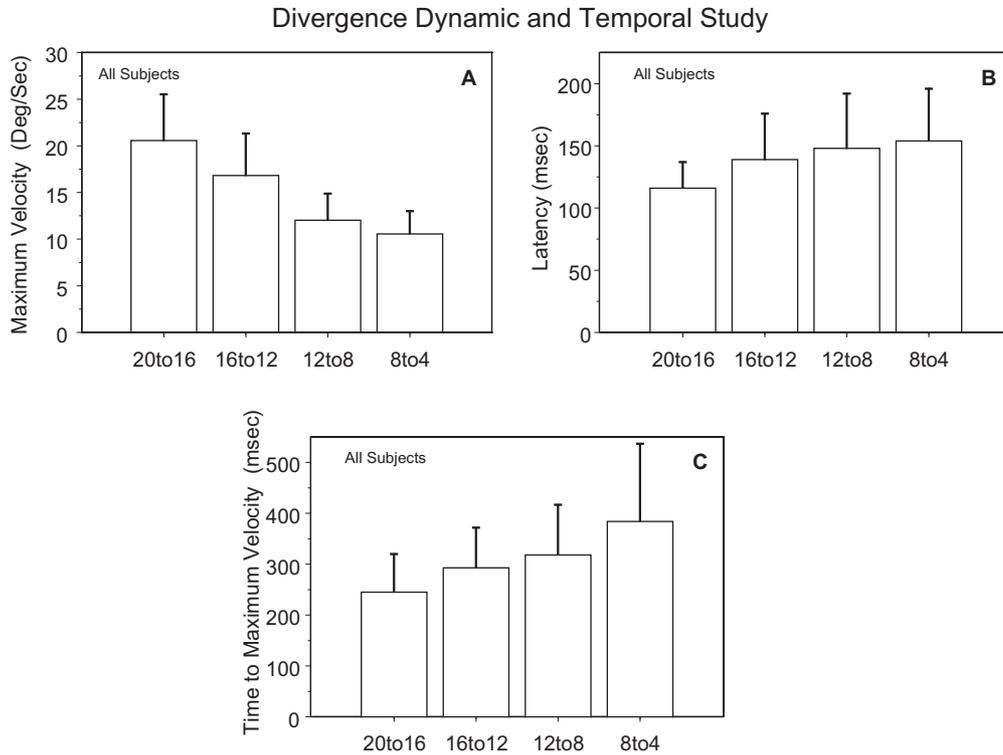


Fig. 3. Dynamic and temporal analysis of all subjects for divergence movements from the following initial positions: 20°, 16°, 12° and 8°. For subject 001, the closest initial position was 18° and is not included in the summary plots above for the 20–16 movement but is included for the other stimuli. Divergence responses are dependent on initial position. All disparity movements are to a 4° step change; however, stimuli closer to the subject evoked faster movements as quantified by an increase in maximum velocity (graph A) and a decrease in temporal properties: the latency (graph B), and time to maximum velocity (graph C).

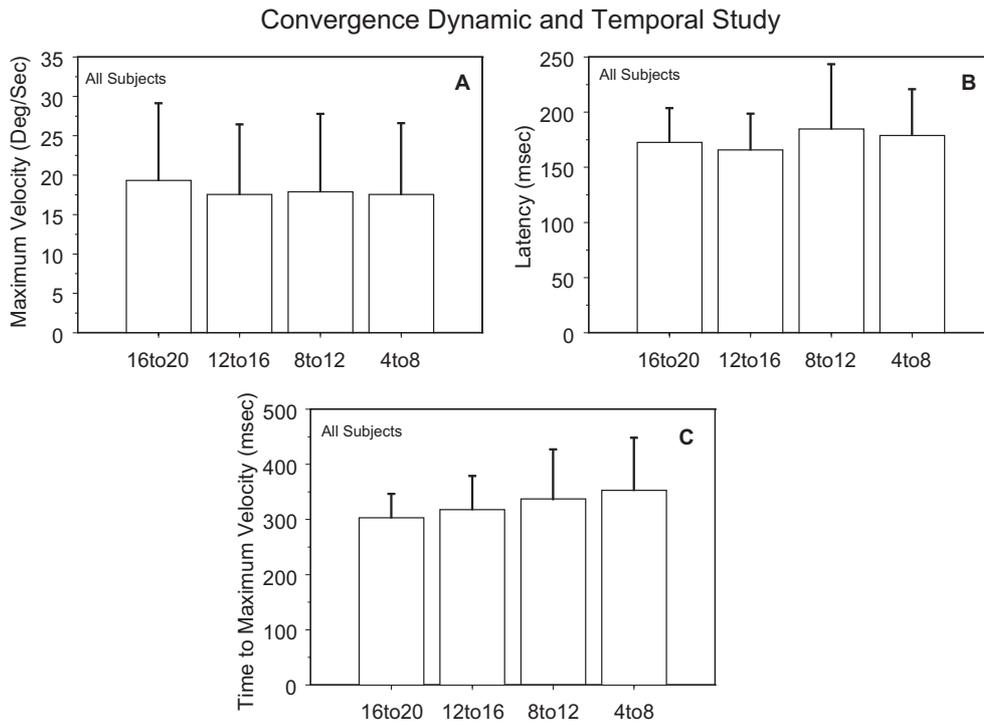


Fig. 4. Dynamic and temporal analysis of convergence eye movements for different initial conditions. No consistent trends existed for all four subjects. Note subject 001 could not perform a convergence movement beginning at 16° and is not included in the summary plots for the 16–20 position. Subject 001 is included in other categories.

Table 4

Statistical Analysis of 4° data when comparing the far stimulus (4–8° for divergence and 8–4° convergence) to the near stimulus (16–20° for divergence or 20–16 for convergence)

Subject	Deg freedom (df)	Statistics for velocity		Statistics for latency		Statistics for time to Vmax	
		<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>
<i>Divergence</i>							
001	27	5.1486	<0.0001	1.0395	0.3078	1.5513	0.1325
002	41	8.2915	<0.0001	1.3580	0.0232	3.0194	0.0043
003	28	10.048	<0.0001	5.4744	<0.0001	3.3424	0.0024
004	77	12.103	<0.0001	4.5952	<0.0001	14.2861	<0.0001
<i>Convergence</i>							
001	61	1.8759	0.0655	0.5438	0.5885	2.5164	0.0145
002	32	7.5676	<0.0001	0.3332	0.7412	1.6661	0.1055
003	71	2.6651	0.0095	1.4228	0.1592	0.2146	0.8307
004	34	1.6455	0.1091	1.0611	0.2961	0.3111	0.7577

Note for Subject 001 the near stimulus is 12–16 for divergence and 18–14 for convergence because this subject had difficulties fusing the 20° stimulus.

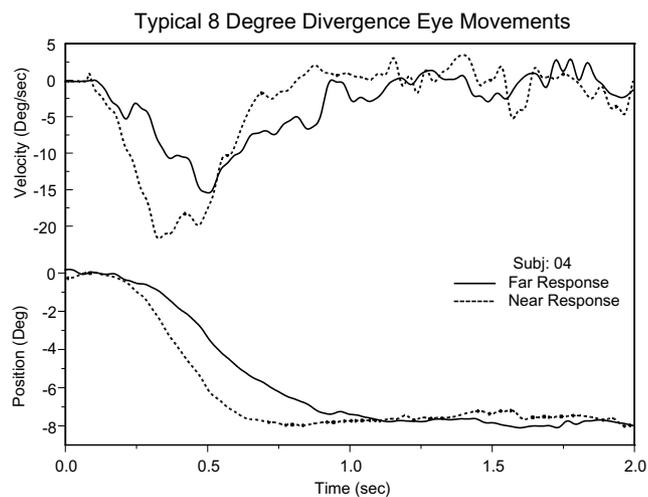


Fig. 5. Typical 8° divergence movement from subject 004 where vergence position is plotted in the lower traces (°) and velocity is plotted in the upper traces (°/s). Similar to the 4° responses, the far response (solid line) to a stimulus beginning at an initial position of 8° exhibited slower dynamics and longer temporal properties compared to the response to a near stimulus (dashed line) which began at an initial position of 20°.

has a longer length and cross section compared to the lateral rectus and thus weighs more as well (Burian & von Noorden, 1985). Perhaps these physiological differences in the medial and lateral recti muscles may lead to nonlinearities in the kinematics of the muscles which may explain why divergence movements are dependent on the stimulus initial conditions.

Table 5

Dynamic and temporal analysis of 8° divergence movements with standard deviation (STD) and the number of samples (*N*) for subject 004

Stimulus	<i>N</i>	Maximum velocity (°/s) ± STD	Latency (ms) ± STD	Time to Vmax (ms) ± STD
20–12	18	26.41 ± 9.05	136 ± 36	370 ± 50
16–8	11	18.72 ± 4.61	140 ± 40	391 ± 99
12–4	8	13.92 ± 1.91	196 ± 49	454 ± 51
8–0	11	12.95 ± 4.26	199 ± 45	480 ± 74

#### 4.3. Differences explained by controller

Based on primate neurophysiologic studies, it has been shown that different cells exist for convergence and divergence movements (Mays, 1984; Mays & Porter, 1984; Mays, Porter, Gamlin, & Tello, 1986). These studies show that convergence cells are more prevalent compared to divergence cells in the midbrain specifically within the mesencephalic reticular formation (Mays et al., 1986). Thus, divergence is not simply a negative convergence movement but a separate neurophysiological system. The neuro-control strategy of the two systems may be different. Evidence of burst and burst-tonic cells show that combinations of a transient and a sustained neural signal are used for both convergence and divergence movements. The divergence cells may fire with more synchronization for near stimuli creating a pulse with a greater magnitude and stronger kinematics compared to divergence responses to stimuli further from the subject. It is also possible that the divergence cell pool may be dependent on the initial position and thus different cells are responsible for stimuli at different distances from the subject.

The Dual Mode Theory was developed using mostly convergence data. Modeling simulations show that convergence is composed of a pulse-step control structure similar to that found in the saccadic system. (Horng, 1994; Horng et al., 1998a, Horng, Semmlow, Hung, & Ciuffreda, 1998b; Hung et al., 1986) However, fewer studies exist to describe the control structure for divergence. Horng postulates in his dissertation that diver-

gence is composed mainly of a step response. He further speculates that a pulse may be present but it would have smaller amplitude than the pulse found in convergence. He does not report the initial vergence position of the stimuli.

Our laboratory has begun a preliminary independent component analysis study. These preliminary results suggest that a pulse is present during divergence movements that are stimulated by near targets but the amplitude of this pulse decreases as the stimulus is moved further from the subject. These preliminary findings agree with Horng's speculations about the control structure of divergence. Further study is needed to determine if this trend is consistent in multiple subjects.

Further study is also needed to determine if the difference in divergence kinematics is due to the extraocular muscles, the controller or a combination of both.

## 5. Conclusion

The dynamics of divergence eye movements are dependent on the initial stimulus position. The closer the stimulus is to the subject, the faster and quicker the responses as quantified by the maximum velocity, the latency, and the time to maximum velocity. Convergence is not dependent on the initial stimulus position.

## Acknowledgment

This research was supported in part by Essilor International.

## References

- Alvarez, T. L., Semmlow, J. L., Yuan, W., & Munoz, P. (2002). Comparison of disparity vergence system responses to predictable and non-predictable stimulations. *Current Psychology of Cognition*, *21*, 243–261.
- Bahill, A. T., Kallman, J. S., & Lieberman, J. E. (1982). Frequency limitation of the two-point central difference differentiation algorithm. *Biological Cybernetics*, *45*, 1–4.
- Burian, H. M., & von Noorden, G. K. (1985). *Binocular vision and ocular motility theory and management of strabismus*. Saint Louis: C.V. Mosby Company (pp. 43–44 and 56–57).
- Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1995). Voluntary binocular gaze-shifts in the plane of regard: Dynamics of version and vergence. *Vision Research*, *35*, 3335–3358.
- Horng, J.-L. (1994). Dynamic model of vergence eye movements. Ph.D. Dissertation, Rutgers University, pp. 123–132.
- Horng, J.-L., Semmlow, J. L., Hung, G. K., & Ciuffreda, K. J. (1998a). Initial component control in disparity vergence: a model-based study. *IEEE Transactions on Biomedical Engineering*, *45*, 249–257.
- Horng, J.-L., Semmlow, J. L., Hung, G. K., & Ciuffreda, K. J. (1998b). Dynamic asymmetric in disparity convergence eye movements. *Vision Research*, *38*, 2761–2768.
- Hung, G. K. (1998). Saccade-vergence trajectories under free- and instrument-space environments. *Current Eye Research*, *17*, 159–164.
- Hung, G. K., Ciuffreda, K. J., Semmlow, J. L., & Horng, J.-L. (1994). Vergence eye movements under natural viewing conditions. *Investigative Ophthalmology and Visual Science*, *35*, 3486–3492.
- Hung, G. K., Semmlow, J. L., & Ciuffreda, K. J. (1986). A dual-mode dynamic model of the vergence eye movement system. *IEEE Transactions on Biomedical Engineering*, *33*, 1021–1028.
- Hung, G. K., Zhu, H., & Ciuffreda, K. J. (1997). Convergence and divergence exhibit different response characteristics to symmetric stimuli. *Vision Research*, *37*, 1197–1205.
- Krishnan, V. V., Farazia, F., & Stark, L. (1973). An analysis of latencies and prediction in the fusional vergence system. *American Journal of Optometry and Archives of American Academy of Optometry*, *50*, 933–939.
- Mays, L. E. (1984). Neural control of vergence eye movements: Convergence and divergence neurons in midbrain. *Journal of Neurophysiology*, *51*, 1091–1108.
- Mays, L. E., & Porter, J. D. (1984). Neural control of vergence eye movements: Activity of abducens and oculomotor neurons. *Journal of Neurophysiology*, *52*, 743–761.
- Mays, L. E., Porter, J. D., Gamlin, P. D. R., & Tello, C. A. (1986). Neural control of vergence eye movements: Neurons encoding vergence velocity. *Journal of Neurophysiology*, *56*, 1007–1021.
- Rashbass, C., & Westheimer, G. (1961). Disjunctive eye movements. *Journal of Physiology*, *159*, 339–360.
- Rosenfield, M., & Ciuffreda, K. J. (1991). The effect of surround propinquity on the open-loop accommodative response. *Investigative Ophthalmology and Visual Science*, *32*, 142–147.
- Semmlow, J., & Wetzel, P. (1979). Dynamic contributions of the components of binocular vergence. *Journal of the Optical Society of America*, *69*, 639–645.
- Yang, Q., Bucci, M. P., & Kapoula, Z. (2002). The latency of saccades, vergence, and combined eye movements in children and in adults. *Investigative Ophthalmology and Visual Science*, *43*, 2939–2949.
- Yuan, W., Semmlow, J. L., & Munoz, P. (2000). Effects of prediction on timing and dynamics of vergence eye movements. *Ophthalmic Physiological Optics*, *20*, 298–305.
- Zee, D. S., Fitzgibbon, E. J., & Optican, L. M. (1992). Saccade-vergence interactions in humans. *Journal of Neurophysiology*, *68*, 1624–1641.