

Effects of visual distractors on vergence eye movements

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Visual attention is an important aspect of everyday life, which can be incorporated in the assessment of many diagnoses. Another important characteristic of visual attention is that it can be improved via therapeutic interventions. Fifteen subjects with normal binocular vision were presented with visual distractor stimuli at various spatial locations while initiating disparity vergence eye movements (inward or outward rotation of eyes) within a haploscope system. First, a stationary distractor stimulus was presented in either the far, middle, or near visual spaces while the subjects were instructed to follow a target stimulus that was either stationary, converging (moving toward subject), or diverging (moving away from subject). For the second experiment, a dynamic distractor stimulus within the far, middle, or near visual space that was converging or diverging was presented while the target stimulus was also converging or diverging. The subjects were instructed to visually follow the target stimulus and ignore the distractor stimulus. The vergence responses had a final vergence angle between the target and distractor stimuli which has been termed a center of gravity (CoG) effect. Statistically significant differences were observed between the convergence peak velocities ($p < 0.001$) and response amplitudes ($p < 0.001$) comparing responses without distractors to responses with the presence of a vergence distractor. The results support that vergence eye movements are influenced by visual distractors, which is similar to how distractors influence saccadic eye movements. The influence of visual distractors within vergence eye movements may be useful to assess binocular dysfunction and visual distraction which are common post brain injury.

complex as rain falling within one's visual field while driving on an urban road. Human eye movement studies on visual distractors have been conducted since the mid-1970s. However, prior research has been exclusively conducted studying the impact of visual distraction on saccadic eye movements (Coëffé & O'regan, 1987; Coren & Hoenig, 1972; Di Russo, Pitzalis, & Spinelli, 2003; Khan, McFadden, Harwood, & Wallman, 2014). Studies have yet to systematically quantify the effects of visual distractors on vergence eye movements, the inward or outward rotation of the eyes to see objects located at different spatial depths. Our world is not a two-dimensional field, but rather three-dimensional where spatial depth is an important visual cue. Hence, a systematic study on vergence eye movements is important to gain an understanding of how visual distractors influence eye movements that are utilized to assess objects located at different spatial depths. This study will concentrate on investigating the effects that visual distractors in three-dimensional space have on vergence eye movements.

Saccadic movements are rapid conjugate eye movements used to explore the world. The response time for saccades are typically a few milliseconds where these eye movements observe the world without an externally driven feedback system (Becker & Fuchs, 1969). Vergence movements are slow disconjugate eye movements that allow the visual system to fuse targets moving in depth, giving a person the ability to perceive the world in all three dimensions (Alvarez, Semmlow, & Pedrono, 2005). While saccadic and vergence eye movements both utilize the medial and lateral recti muscles to rotate the globes until the paired images are projected onto the foveas, they have both shared and independent neural sites (Alvarez, Semmlow, Yuan, & Munoz, 2000; Alvarez, Alkan, Gohel, Douglas Ward, & Biswal, 2010; Muhammad & Spratling, 2015; Semmlow, Yuan, & Alvarez, 1998).

Introduction

Visual distractors occur in everyday life. They could be as simple as a bee flying across one's face or as

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Prior research studying the impact of distractors on saccadic eye movements report that when a visual distractor stimulus was close to the target stimulus, saccadic eye movements were directed toward the distractor (Findlay & Harris, 1984; Van der Stigchel & Theeuwes, 2005), while a distractor stimulus close to the instructed visual target stimulus resulted in saccades that were closer to the target stimulus (Alvarez et al., 2008; Doyle & Walker, 2001; Van der Stigchel & Theeuwes, 2005). These trends in saccadic eye movements in the presence of a distractor stimulus were described as the center of gravity (CoG) effect, in which the eyes fixated on the geometric center between the target and distractor stimuli (Coëffé & O’regan, 1987; Coren & Hoenig, 1972; Kaufman & Richards, 1969). Similar studies have also identified increases in latencies (Lévy-Schoen, 1969; Walker, Deubel, Schneider, & Findlay, 1997) as well as decreases in peak velocities and eye movement response amplitudes (Deuble, Wolf, & Hauske, 1984; Walker et al., 1997) in saccadic eye movements with a distractor stimulus compared to those without a distractor stimulus.

This investigation will assess the effects of distractors located in three-dimensional space on vergence eye movements. We hypothesize that the vergence eye movements will exhibit a similar CoG effect and reduced peak velocities, which has been described within saccadic eye movements when a distractor stimulus was presented. This research will allow a systematic study of vergence eye movements with and without visual distraction and hence, will enable a quantification of visual attention.

Method

An experimental protocol was designed to examine and quantify the effects of visual distractors on vergence eye movements compared to vergence eye movements without the presence of a visual distractor stimulus. A haploscope setup was utilized for eye movement recordings synchronized with visual stimuli presentation. This setup stimulates disparity vergence, while minimizing proximal vergence cues and holding accommodative visual cues constant. Subject criteria, experimental set-up, protocols, data, and statistical analysis are described below.

Subjects

Twenty subjects participated in this study. Nine subjects were males and eleven were females. Subjects ranged between 18 and 33 years, mean of 21.9 ± 3.7 years. Five subjects were excluded from the study. Three

excluded subjects were not converging onto the target stimulus and were making multiple saccadic movements, one could not fuse the target stimuli, and the last excluded subject was heavily right eye dominant and was making vergence movements with asymmetries where the peak velocity in one eye was more than double the speed of the other. The remaining 15 subjects included eight men and seven women, ranging in age between 18 and 33 years with a mean age of 22.3 ± 4.1 years. All subjects signed informed consent documentation prior to the experiments, which were approved by the New Jersey Institute of Technology’s (NJIT) Institutional Review Board (IRB) in accordance with the Declaration of Helsinki. All participating subjects were naïve to the goals of the study and the operator read a detailed script so that each subject heard the exact same instructions. The specific instructions that were pertinent to this study were the following:

Each trial will begin after you press the red button on the trigger. Prior to the pressing of the trigger, please fuse the X in front of you. Either cross or relax your eyes so that the target X is single and clear. During each trial, please make sure the X and only the X is single and clear. If the target X moves in the trial, either cross or relax your eye so the X is single and clear. You may see other targets during the experiment, please try to ignore them and only look at the X keeping it single and clear.

The experimentation space was equipped with a head and chin rest where the subjects were secured and restrained with an elastic band to reduce the influence from the vestibular system, which is known to influence the vergence system (Khojasteh & Galiana, 2007). Subjects were instructed to depress a button to begin each trial and to maintain binocular fixation for the duration of the trial. The subjects were also asked to restrain from any head movement.

Exclusion criteria

The following criteria were used to determine eligible subjects for the study: (a) subjects had a visual acuity of 20/20 in each eye, (corrective lenses to attain 20/20 vision were used when needed), (b) no history of neurological or ophthalmic disease, dysfunction, or injury, (c) no history of traumatic brain injury (TBI) or concussions, and (d) had clinical measurements to classify as binocularly normal as described in the Clinical measurements section.

Clinical measurements

All subjects were classified to be binocularly normal by an assessment of six vision measurements (Alvarez et al.,

Subject	Stereopsis		Near point of convergence		Near dissociated phoria (Δ)
	Fine (seconds of arc)	Coarse (seconds of arc)	Break (cm)	Recovery (cm)	
1	20	250	5	6	-2
2	20	250	1	2	0
3	25	250	3	4	4
4	40	250	4	6	-8
5	20	250	4.5	5	-3
6	40	250	2.5	4	2
7	40	250	5.5	6.5	-2
8	50	250	5	7	-2
9	25	250	3	4.5	-4
10	20	250	4.5	8	-2
11	40	250	3	4	2
12	20	250	4	7	3
13	30	250	4	5.5	4
14	70	250	3.5	4.5	-7
15	20	250	6	9	-3
Average	32	250	3.9	5.5	-1.2
SD	14.1	0	1.2	1.7	3.6

Table 1. Clinical information: Part 1.

2010). These measurements were taken on the first day of experimentation, as summarized in Tables 1 and 2.

Visual acuity: Visual acuity was measured using a Snellen eye chart. Subjects wore contact or spectacle

lenses if needed throughout all vision and eye movement assessments. Subjects were instructed to stand 6 m away from the chart and read line 8, left to right, with their right eye covered. They were next instructed to read line 8, right to left, with their left eye covered. The number of incorrect letters read were recorded. Normal was defined as two errors or less and all subjects had two errors or less which equates to an acuity of 20/20 vision.

Stereopsis: This measurement was quantified with the Bernell Stereo Randot Test using the Randot Circles (Bernell, South Bend, IN). Stereopsis was quantified by 10 grades ranging from 20 to 400 seconds of arc. Normal was defined as 70 seconds of arc or below and all subjects were assessed to have stereopsis of 70 seconds of arc or better.

Near point of convergence (NPC): The NPC break value was measured by having the operator slowly bring a card with a cross of 20/20 acuity, placed on a Bernell Accommodation Convergence Rule (Bernell, South Bend, IN), toward the subject along their midline. The subject was instructed to maintain fixation on the cross and to keep it single and clear. The subject was asked to report when the cross doubled, the operator would ask the subject if they could make the cross single again. If the subject was able to fuse, the operator continued to slowly move the cross towards the subject (along midline). If the subject was unable to fuse, the distance from the bridge of the nose to the location of the cross was measured with the Accom-

Subject	Vergence range (Δ)						Motor dominance
	Base out			Base in			
	Blur	Break	Recovery	Blur	Break	Recovery	
1	25	40	35	NA	12	10	Right
2	16	45+	45+	14	16	14	Right
3	20	30	25	14	16	14	Right
4	14	16	14	18	20	18	Left
5	20	25	20	NA	14	12	Right
6	30	35	30	12	8	12	Right
7	12	25	20	14	16	14	Right
8	20	30	25	12	14	12	Right
9	NA	18	10	NA	14	12	Left
10	8	14	12	NA	10	8	Right
11	20	20	18	12	12	10	Left
12	30	45+	45+	NA	16	14	Left
13	16	25	20	10	14	12	Right
14	40	45	40	NA	20	16	Right
15	NA	45+	45+	NA	18	14	Right
Average	20.1	26.9	22.4	12.3	14.7	14.7	
SD	8.2	9.2	8.7	1.4	3.2	3.2	

Table 2. Clinical information: Part 2. NA means the subject did not perceive blur of the visual stimulus and hence those data were not included in the average and standard deviation calculations. 45+ means the subject did not perceive diplopia at the maximum prism of 45 Δ within our instrument.

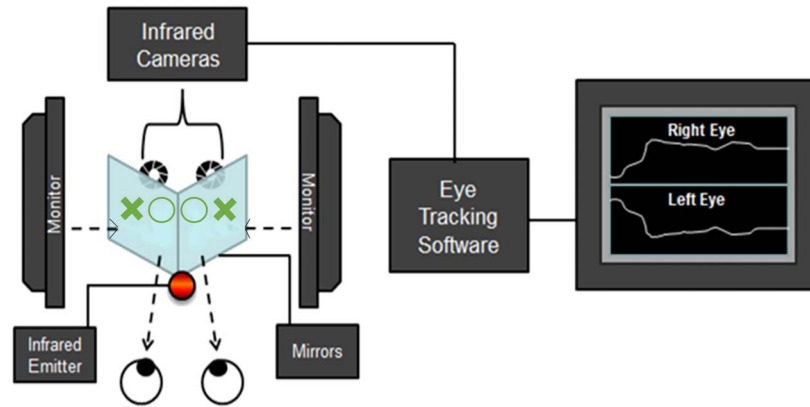


Figure 1. Haploscope system with representations of target X and distractor O stimuli.

modation Convergence Rule in centimeters. Mean NPC breakpoint was 3.9 ± 1.2 cm. Normal was defined as 8 cm or less.

Recovery point of convergence (RPC): RPC was measured immediately after NPC. Once the subject could no longer fuse the cross into a single image, the cross was slowly moved away from the subject along the midline. The subject was instructed to try and fuse the cross into one image and report when the subject was able to achieve a single image. Normal was defined as within 2 cm of NPC breakpoint.

Fusional vergence (FV): Positive and negative fusional vergence (PFV and NFV, respectively) was measured using the Bernell horizontal prism bar using base-out (BO) and base-in (BI) prisms, respectively. The prism bar has 16 prisms: 1Δ , 2Δ to 20Δ (in increments of 2Δ), and 20Δ to 45Δ (in increments of 5Δ). The same cross from the NPC test was held 40 cm away from the subject along their midline and the subject was instructed to maintain fixation on the cross, making it single and clear. The blur point was measured when the subject first reported sustained blur. Once the cross was no longer perceived as a single image, the operator would present the right eye with a prism of a higher diopter. The prism value was recorded when the subject could no longer perceive a single image of the cross, which was noted as the break point. The next harder prism was then placed in front of the subject and the operator ensured the subject reported double vision when viewing the X target. The prism was decreased in magnitude until the subject reported single vision. This was recorded as the recovery point of FV. The mean break PFV was $26.2\Delta \pm 9.2\Delta$ and the mean break NFV was $14.8\Delta \pm 2.7\Delta$.

Phoria: Dissociated near (40 cm away along the subject's midline) phoria was subjectively measured using a flashed Maddox rod procedure (Kim, Granger-Donetti, Vicci, & Alvarez, 2010). A muscle imbalance measure (MIM; Bernell) card with a resolution of 1Δ

and range of 28Δ exophoria to 28Δ esophoria was used to assess phoria. The MIM card was calibrated for the Maddox rod to be placed over the right eye. Normal was defined to be between 8Δ exophoria and 4Δ esophoria. Esophoria was recorded as positive and exophoria was recorded as negative values in the tables below.

Oculomotor dominance was not used in the assessment of normal binocular vision but was measured using the Miles technique. The subject would fixate on the X high acuity target situation about 40 cm away from the subject's midline. The subject would then form an aperture with their hands which would be slowly reduced in size until only the X was perceived through the visual aperture created by the hands. The eye which viewed the visual target was denoted as the dominant eye.

Experimental setup

Vergence disparity visual stimuli were presented to the subjects via a haploscope system (Figure 1). Two computer monitors, one for each eye, were used to present symmetrical vergence disparity stimuli. The target and distractor stimuli were projected onto the subject's field of view by two partially reflective (50% light transmission) mirrors. The subject was carefully situated in the apparatus so that all visual stimuli were along the subject's midline, the midsagittal plane. All stimuli that were presented within the haploscope were calibrated with physical targets placed at measured distance to evoke the following vergence angles: 1° , 3° , 5° , 7° , and 9° . The voltage values at these vergence angles were recorded to form linear relationships between vergence angles and voltage output. The subjects were placed in a customized space and covered by commercial blackout curtains (Blackout Curtains, St. Louis Park, MN) to minimize the amount of light

emitted into the experimentation space. Prior to the start of each experimental session, each subject verbally confirmed that he or she did not perceive any light source other than the presented stimuli.

Eye movements were recorded with an ISCAN Eye Tracking Camera System (model ETL 400; ISCAN Inc., Burlington, MA). This system utilizes an infrared ($\lambda = 950$ nm) video-based system. The manufacturer specifies that the accuracy for this system is 0.3° over a $\pm 20^\circ$ horizontal range. The two cameras were placed in front of subject, one in front of the left eye and the other in front of the right eye at a distance of 38 cm, which is the distance recommended by the manufacturer. The cameras have a clear line of sight to the subject's eyes and were not blocked by any materials including the partially reflective mirrors. Individual eye movements were quantified using the centroid of the pupil movements at a sampling rate of 240 frames per second (fps). Each subject's eyes were illuminated using a board beam infrared source. The maximum infrared light power level was 1.2 mW/cm^2 , which is well below the ANSI Z136 specification safety limits of 10 mW/cm^2 .

The entire system was controlled by a custom LabVIEW™ 2013 SP 1 Virtual Instrument (National Instrument, Austin, TX) called VisualEyes2020 which generated the visual stimuli that was digitally synchronized with the eye movement acquisition to ensure accurate temporal analyses. This system was a modified version of the 2011 system described by Guo, Kim, and Alvarez (2011). Prior research calculated via a spectrum analysis showed that the power of saccadic eye movements are predominantly within the first 100 Hz (Zuber, Semmlow, & Stark, 1968). Since vergence eye movements are an order of magnitude slower than saccadic eye movements, our sampling rate of 240 fps satisfies the Nyquist criterion for digitizing both saccadic and vergence eye movements. While vergence eye movements were the primary purpose of this investigation, it is well known that even with symmetrical vergence stimuli, saccadic responses are commonly initiated (Jaswal, Gohel, Biswal, & Alvarez, 2014; Semmlow, Chen, Granger, Donnetti, & Alvarez, 2008). The signals were digitized using a 16-bit digital acquisition (DAQ) hardware card using the range of ± 5 Volts (National Instruments PCIe-6351 X Series Data Acquisition, Austin, TX). The left- and right-eye movements were saved individually for offline data analysis using a custom MATLAB version R2015A code (MathWorks, Natick, MA).

Experimental design

The experiment was divided into two phases to reduce the experimental time for each session to about one hour and hence reduce visual fatigue (Alvarez et

al., 2010; Alvarez, Semmlow, Yuan, & Munoz, 2002; Alvarez, Bhavsar, Semmlow, Bergen, & Pedrono, 2005). Each phase was repeated twice (Sessions 1 and 2) so that subjects participated in a total of four experimental sessions. The target stimuli for this experiment was an X and the distractor stimuli was an O, both of which have a width and height of 1.5° .

A schematic of the visual experimental stimuli is presented in Figure 2 where the instructed visual target stimulus (the X) and the distractor stimulus (the O) are shown as solid red and dashed blue lines, respectively. The target X stimulus and distractor O stimulus are similar to the ones used in multiple saccadic distractor studies (Van der Stigchel & Theeuwes, 2005; Walker et al., 1997). The monocular position of each target and distractor stimuli in the 24 types of movements with visual distractor stimuli and four types of controls baseline eye movements without distractors are displayed in Figure 2. Phase 1 consists of only one dynamic (moving) stimulus, either the target or distractor but not both. Whereas, Phase 2 has both the target and distractor stimuli moving. Baseline control movement types 1 and 2 with no distracting stimulus are measured within Phase 1, while baseline control movement types 3 and 4 with no distracting stimulus are measured within Phase 2. All 28 movements (four control and 24 types with distractors) were 2.5 s in duration. In movements where a step is involved, the step occurs after 1 s, allowing the subject 1.5 s to fuse on the target stimulus located at the new vergence angle location. Prior research has shown 1.5 s is adequate to have a person fuse on a vergence target stimulus for binocularly normal controls (Alvarez, Semmlow, & Yuan, 1998; Alvarez et al., 2000).

Stimuli within each phase were presented to the subject in a pseudorandom manner to reduce prediction. A random delay of 0.5–1.5 s was additionally presented after the trigger press to further reduce any potential anticipatory movements. Anticipation alters vergence peak velocity and latency (Alkan, Alvarez, Gohel, Taylor, & Biswal, 2011; Alvarez, Bhavsar, et al., 2005; Alvarez et al., 2002). Convergence movements were defined as the positive (direction) movements and divergence movements were plotted in the negative direction.

Each experimental session was subdivided into three identical stages. Each stage began with a calibration. The calibration consisted of eight stimulations at 1° , 3° , 7° , and 9° for each eye, for an eight-point monocular calibration to reduce potential error that could be introduced via fixation disparity. The calibration phase was followed by five pseudorandom presentations of each stimulus within their respective phase. At the end of each stage, the subject was given a 5-minute break to reduce any potential visual fatigue. The subject was presented with each stimuli combination a total of 15 times on each day, yielding a total of 30 trials for each type of movement

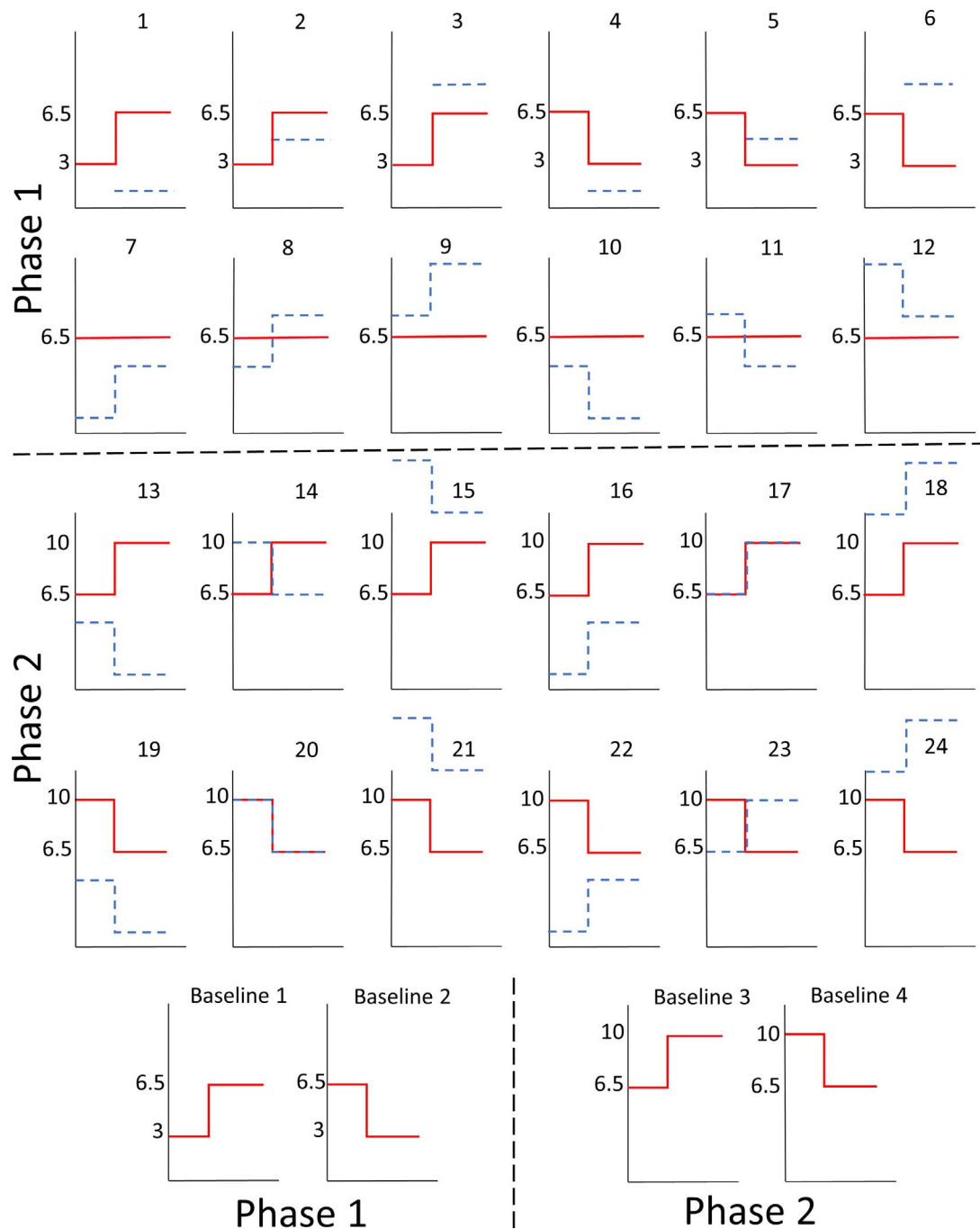


Figure 2. Target (red solid line) and distractor (blue dashed line) stimulus presentation location in monocular degrees. Phase 1 contains only one dynamic (moving) stimulus, while Phase 2 contains two dynamic stimuli. The bottom four baseline illustrations are presentations of the target stimulus locations without any distractor stimulus.

since Phases 1 and 2 were each repeated twice, with repeats referred to as Sessions 1 and 2.

Data analysis

Data processing

Data were analyzed offline using a custom MATLAB version R2015a code (MathWorks). Disconjugate

vergence movements were calculated by subtracting the right eye position data from the left eye position data. Raw positional data were converted into angular position using linear relationships from the respective monocular calibration within the experimental session. The individual movements were then filtered using a sixth-order low pass Butterworth filter with a cut off frequency of 40 Hz. Disconjugate eye movements were plotted along with position of target and distractor

Phase Plane Analysis to Objectively Calculate Response Amplitude

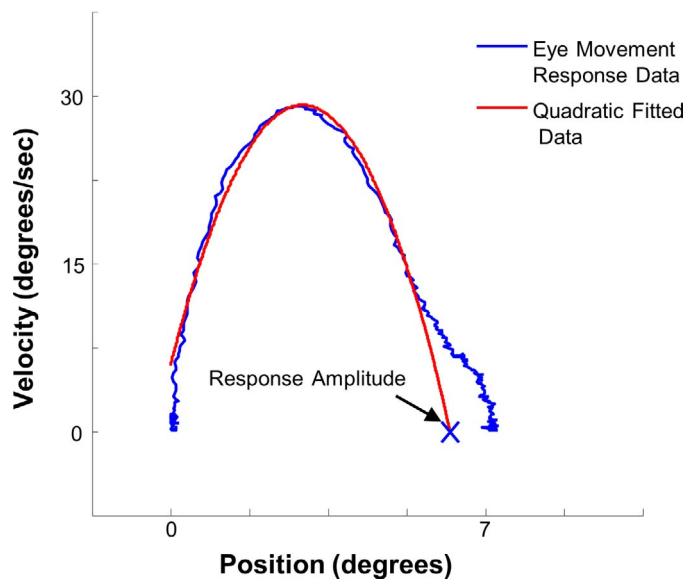


Figure 3. Data analysis showing how experimental vergence eye movement response (blue line) was fit with a quadratic (second order polynomial) equation (red line) and the non-zero root (blue X) was calculated as the response amplitude (labeled by arrow).

stimuli to determine which of the trials would be used for further analysis. Saccades of 0.3° (the resolution of our eye movement system) were automatically identified by our previously published studies and then confirmed by the data analyst (Kim & Alvarez, 2012; Semmlow et al., 2008; Semmlow, Chen, Pedrono, & Alvarez, 2007). All disconjugate movements that had saccades or eye blinks (identified as signal saturation) within the transient portion of the eye movement were omitted (between 4.7% to 8.9% of movements, depending on the subject) from further analysis because it has been shown that saccades increase vergence peak velocity (Alvarez & Kim, 2013; Zee, Fitzgibbon, & Optican, 1992). Additionally, any disconjugate trials which had movements that deviated by more than 2° (50% of the intended visual stimuli) from the stimulus (target or distractor) were eliminated, although this was a rare occurrence (about 0.5% of movements). All eye movements were analyzed individually and then the data were pooled for a group level analysis.

The mean and standard deviations were calculated for the remaining trials for each of the movements on an individual subject basis. Velocity traces were generated for each trial by computing the average eye velocity for each point in time using a two-point central difference algorithm. Means and standard deviations were additionally calculated for the velocity traces of

Group	Movement type	Associated baseline control	Target stimulus to track	Distractor
1	1, 2, and 3	1	Converging	Stationary
2	4, 5, and 6	2	Diverging	Stationary
3	13, 14, and 15	3	Converging	Diverging
4	16, 17, and 18	3	Converging	Converging
5	19, 20, and 21	4	Diverging	Diverging
6	22, 23, and 24	4	Diverging	Converging

Table 3. Statistical groups with movement types described in Figure 2.

each type of movement. Response amplitudes were measured within the phase plane which was a plot of the individual trial's position as a function velocity. Figure 3 shows an experimental vergence eye movement data response (blue line) that was fit with a quadratic (second-order polynomial) equation (red line). The non-zero root was chosen as the response amplitude shown as an X and labeled with an arrow stating response amplitude in Figure 3. This methodology has been utilized in prior studies from our laboratory (Alvarez, Kim, & Granger-Donetti, 2017; Alvarez, Kim, Yaramothu, & Granger-Donetti, 2017; Alvarez et al., 1998; Lee, Chen, & Alvarez, 2008). It is beneficial because it is objective and hence reduces potential bias from the data analyst.

Statistical analysis

Paired t tests ($\alpha = 0.05$) and the interclass correlation coefficients (ICC) were calculated for the four baseline movements datasets pooled across the subjects to compare the data between Sessions 1 and 2. A univariate repeated measures ANOVA was used for assessing statistical significance of the peak velocity and response amplitudes of the different experimental conditions. Sphericity was checked between all pairs using Mauchly's test during the ANOVA. If the group did not pass Mauchly's test, Greenhouse-Geisser's method was used for all subsequent ANOVA measures for that group. Group level scores for peak velocity and response amplitude were calculated by obtaining the means of the trials from each subject. Statistical analyses were reported for 18 of the movement types that showed significant differences with the control movements with no distracting stimuli. The 18 movements were subdivided into six groups, each with its respective control movements, for the ANOVAs as described in Table 3. Post hoc pairwise comparisons using a paired-samples t test with alpha adjusted to protect significance with the Bonferroni correction was used on all significant ANOVA groups.

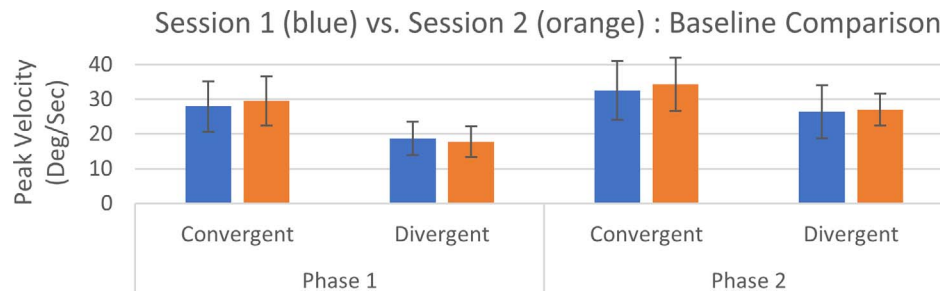


Figure 4. Baseline (target stimulus with no distractor stimulus) peak velocity Session 1 compared to Session 2.

Results

The baseline movements for Sessions 1 and 2 were assessed using a paired *t* test and an ICC. The results in Table 4 show that the peak velocities of the baseline movements on both days were not statistically different. Additionally, the baseline peak velocities on both days had a high ICC ranging from 0.80 to 0.88. This range ($0.75 < ICC < 1.00$) is stratified by statisticians as excellent (Cicchetti, 1994). The group level mean peak velocities were plotted in Figure 4 to visualize the similarities between Sessions 1 and 2. The ICC values for movement types 1, 2, and 3 were 0.84, 0.88, and 0.81, respectively, when compared between Sessions 1 and 2. Due to the high repeatability of data from both days, the baseline data were pooled and all further analysis was conducted on the combined data.

The effects of stationary visual distractors during vergence movements can be observed in the mean group level peak velocity and response amplitudes shown in Figure 5. The peak velocity and response amplitudes portray similar trends. While the eyes are making a convergent movement, moving from far to near, the far distractor stimulus had the greatest effect on peak velocity and response amplitude when compared to the baseline control movement (vergence eye movement without any distractor present). The control peak velocity was $28.7^\circ/s \pm 6.5^\circ/s$ compared to when the far distractor was present where the peak velocity was $16.5^\circ/s \pm 5.9^\circ/s$. The middle and near distractor locations also exhibited some effect on the means of peak velocity and response amplitude, in relation to the baseline, where there is no distractor stimulus. The opposite however, is true for the

divergent movements with a distractor. A near distractor had the greatest effect on both parameters of peak velocity and response amplitude when a divergent movement was initiated. The control peak velocity and response amplitude was $18.3^\circ/s \pm 4.3^\circ/s$ and $5.9^\circ \pm 0.8^\circ$, respectively, compared to when the near distractor stimulus was present where the peak velocity and response amplitude was $14.0^\circ/s \pm 3.7^\circ/s$ and $3.7^\circ \pm 1.6^\circ$, respectively. A greater effect can be observed in the response amplitude than the mean peak velocities. A diminishment of this effect can also be observed in the middle and far distractor locations. Thus, the presentation of a distractor stimulus in the opposite direction of the target stimulus movement yielded the greatest effect in mean peak velocities and response amplitudes.

The effects of stationary visual distractors in vergence movements can be observed in the individual traces of Subject 6 in Figure 6 and in the mean disconjugate positional traces of all the subjects of the six movement types shown in Figure 7. The solid blue traces represent the mean disconjugate eye position of all 15 subjects, with the lighter blue shading showing one standard deviation. Green traces show the mean velocity. The solid red and dashed cyan line show the position of the visual target and distractor stimuli, respectively. The eye movements in Figures 6 and 7 depict similar trends that are quantified in Figure 5. The greatest impact on the peak velocity and response amplitude of vergence eye movements are present when the distractor stimulus is presented in the opposite direction of the target stimulus; such as in movements types 1 and 6, where the stationary distractors stimuli are the maximum distance away from the target stimulus. A repeated measure ANOVA analysis on peak velocity (PV) and response amplitude (RA) on the two groups of convergence [PV: $F(3, 42) = 106, p < 0.001$; RA: $F(1.4, 19.3) = 43, p < 0.001$] and divergence [PV: $F(3, 28) = 28, p < 0.001$; RA: $F(1.7, 24.3) = 35, p < 0.001$] yielded a significant difference between the control vergence eye movement (no distractor) and vergence eye movements with distractors, as shown in Table 5.

	Phase 1		Phase 2	
	Convergent	Divergent	Convergent	Divergent
Paired <i>t</i> test	-1.02	-0.96	-1.37	0.47
Significance	0.33	0.35	0.19	0.65
ICC	0.80	0.80	0.88	0.83

Table 4. Day 1 versus Day 2 control movements peak velocity comparison.

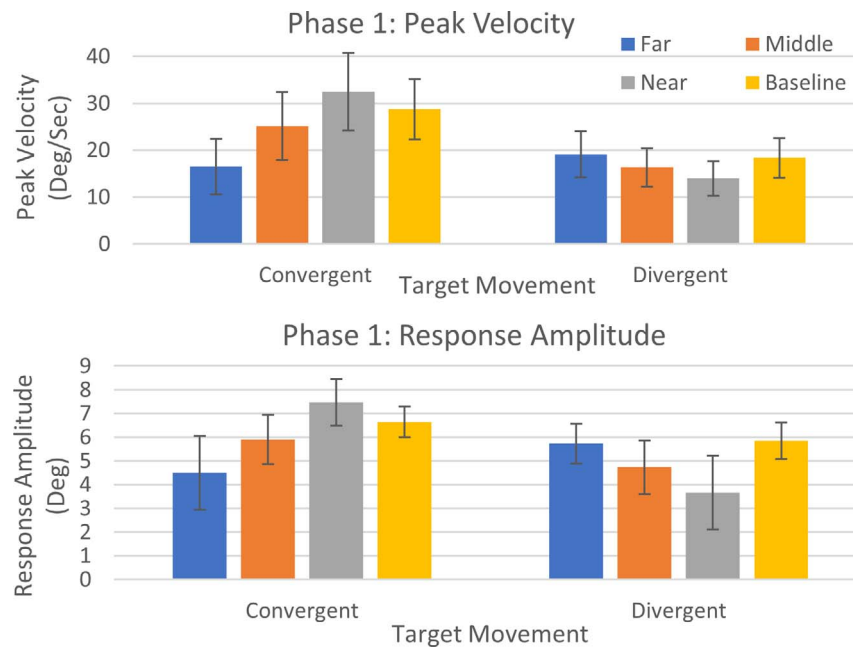


Figure 5. Phase 1 peak velocity and response amplitude where the target stimulus was either converging or diverging and the distractor stimulus was stationary.

A post hoc pairwise *t* test analysis (alpha adjusted with Bonferroni correction) on the convergent movement’s parameters yielded a significant difference of the peak velocity and response amplitude in all six pairs as shown in Tables 6 and 7. Each of the convergent movements with a stationary distractor (Movement types 1, 2, and 3) and baseline control with no distractor were statically different from each other. Regardless of the position of a distractor during convergent movements, the eye movements were statistically different. Additionally, the location of a distractor significantly affected the eye movements to varying degrees.

The same post hoc analysis on divergent movements showed significant differences in five of the six pairs

(movements with distractor stimuli compared to control movements without distractor) for peak velocity and response amplitude as shown in Tables 6 and 7. Movement types 4, 5, and 6 (diverging target stimuli, stationary distractor) had a significance of $p < 0.01$ when each of the movements’ peak velocity and response amplitude were compared with each other. Movement types 5 and 6 (middle and near distractor stimuli, respectively) likewise had a significance of $p < 0.01$ when their parameters were compared to the baseline control movement that did not have distractors present. The only pair to not show significance (PV: $p = 0.248$; RA: $p = 0.225$) was movement type 4 (diverging target stimuli with far stationary distractor) being compared to the baseline. Contrary to the convergent movements, not all

Group	Phase 1		Phase 2			
	Stationary distractor		Converging distractor		Diverging distractor	
	Converging target 1	Diverging target 2	Converging target 4	Diverging target 3	Converging target 6	Diverging target 5
Peak velocity						
<i>F</i> value	106.12	28.31	48.67	24.42	21.59	22.41
Significance	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>df</i>	3, 42	3, 42	2.2, 30.9	3, 42	1.7, 24.4	3, 42
Resp. Amp.						
<i>F</i> Value	43.03	35.50	24.13	30.39	15.18	10.57
Significance	<0.001	<0.001	<0.001	<0.001	0.001	0.004
<i>df</i>	1.4, 19.3	1.7, 24.3	1.0, 14.7	1.4, 19.6	1.2, 17.5	1.1, 16.0

Table 5. Repeated measures ANOVA.

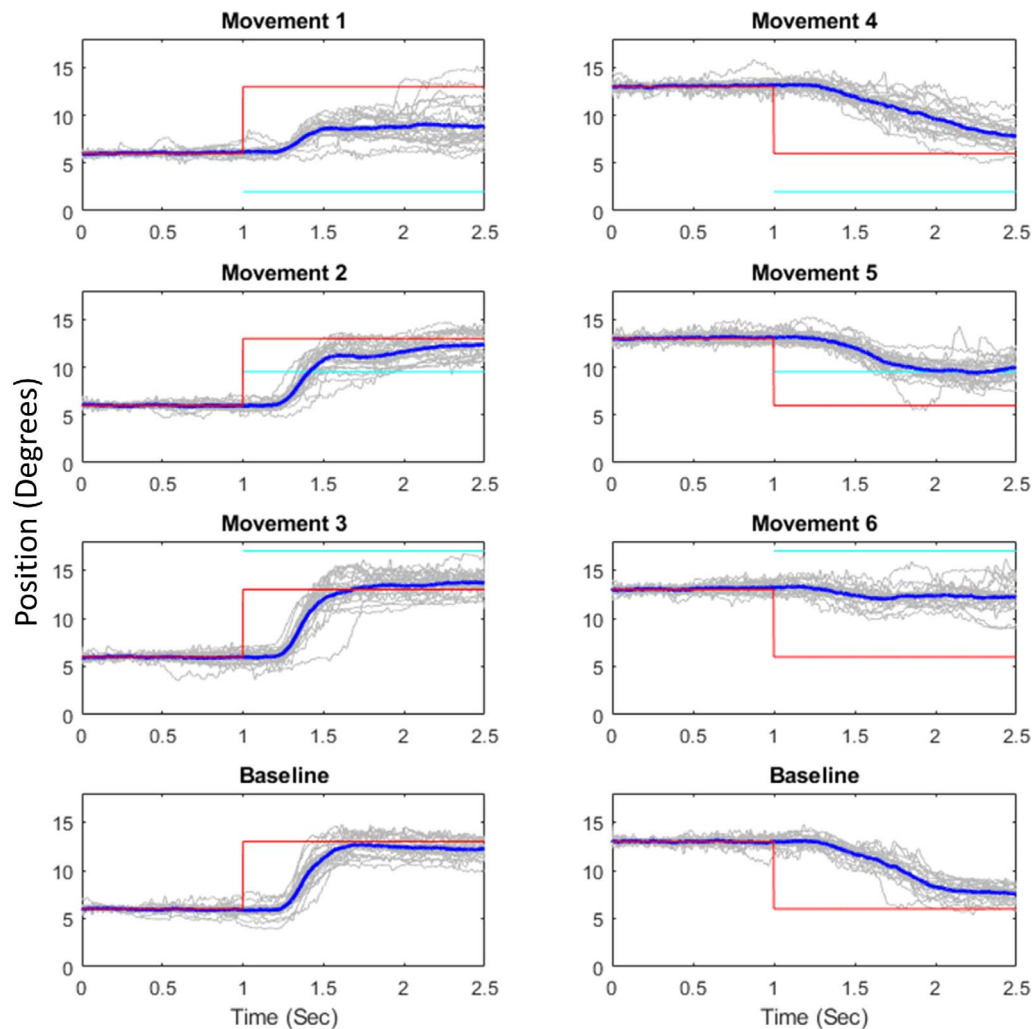


Figure 6. Phase 1 ensemble vergence eye movements of one subject (gray traces) with the mean movement overlay (blue line). The target stimulus to track is plotted in a solid red line and the position of the distractor stimulus is plotted in a solid cyan line.

stationary distractor positions yielded a statistically significant effect on divergent movements.

Unlike stationary distractor stimuli, dynamic (moving) distractor stimuli (Phase 2) had a reduced effect on vergence movements. A distractor stimulus in the opposite direction of the target stimulus still yielded the greatest effect in mean peak velocities and response amplitudes when compared to the baseline control eye movement condition. Figure 8 displays the mean peak velocity and response amplitude of all 15 subjects in Phase 2, which contained a dynamic distractor stimulus with a dynamic target stimulus. The greatest differences in the mean parameters were present in movements with a converging target stimulus. Additionally, a divergent distractor stimulus had a greater effect on the convergent movement, compared to the converging distractor stimulus.

The mean disconjugate eye movements in Figure 9 best exemplify the trends shown in Figure 8 regarding moving distractor stimuli. The traces and color schemes in Figure 9 utilize the same nomenclature as Figure 7. A

greater standard deviation of the disconjugate eye movement can be observed, when there is a larger effect by the distractor. This shows how variability in the movements can be stimulated by a distractor. The movements with the greatest deviation (movement types 13, 16, 21, and 24) also had the highest standard deviation once the movement began. A repeated measure ANOVA performed on the peak velocity (PV) and response amplitude (RA) on the two groups of convergent movements with a converging distractor [PV: $F(2.2, 30.9) = 49, p < 0.001$; RA: $F(1, 14.7) = 24, p < 0.001$] and diverging distractor [PV: $F(3, 42) = 24, p < 0.001$; RA: $F(1.4, 19.6) = 30, p < 0.001$] and two groups of divergent movements with a converging distractor [PV: $F(1.7, 24.4) = 22, p < 0.001$; RA: $F(1.2, 17.5) = 15, p < 0.001$] and diverging distractor [PV: $F(3, 42) = 22, p < 0.001$; RA: $F(1.1, 16) = 11, p = 0.004$] yielded a significant effect, as shown in Table 5. Each group had a vergence movement with its respective dynamic distrac-

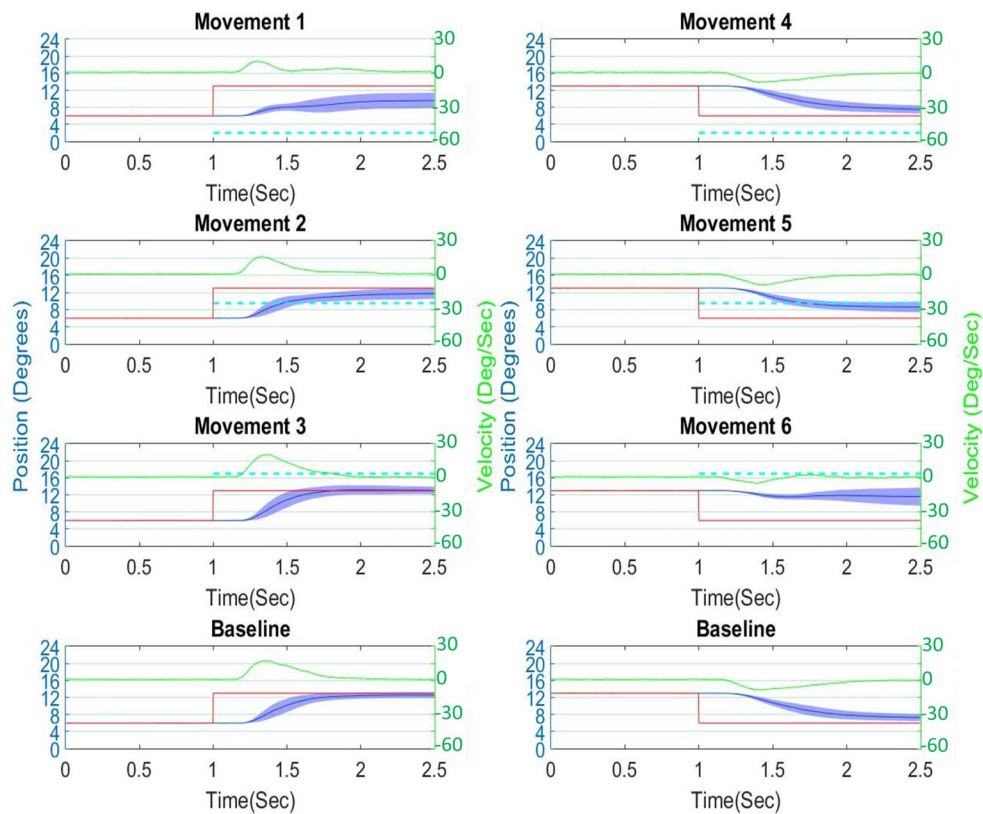


Figure 7. Phase 1 mean disconjugate movements with one standard deviation position (blue trace) velocity (green trace). The target stimulus to track is plotted in a solid red line and the position of the distractor stimulus is plotted in dashed cyan line.

tors in the far, middle, and near spatial locations, in addition to the baseline with no distractor stimulus.

A post hoc analysis on all four groups showed statistically significant differences consistent with the mean plots in Figure 8. Additionally, all pairs that showed significant differences in the peak velocity were also significant in the response amplitude pairs. Unlike the pairs with stationary distractor stimuli, not all movements with dynamic distractor stimuli were statistically significantly different when the alpha was adjusted with the Bonferroni correction. The pairs that did exhibit the largest significant differences were the ones where the vergence movements with no distractor stimulus were compared to the movements where the distractor stimulus was in the opposite location of the target stimulus (movement types 13, 16, 21, and 24). The different vergence directions of the distractor stimulus did not yield varying results. Based on the number of pairs that yielded significant differences, the stationary distractor stimuli also had a greater effect on vergence movements. Specifically, convergent movements were affected more than divergent movements in all scenarios. Finally, movement types 6 to 12, which had dynamic distractor stimuli with a stationary target stimulus showed no effect. There was no significant effect or deviation of the disconjugate eye movements due to the presence of a distractor stimulus at any location.

Discussion

The baseline control movements with no distractor stimulus showed high repeatability between the two sessions of data collection for each phase. Visual distractors did significantly alter the peak velocity and response amplitude in both sessions. This consistency shows the reliability of the effects of vergence distractors. Each of the sessions occurred on different days with at least 24 hours between each session. The significant deviations observed in the vergence eye movements peak velocity and response amplitude can mainly be attributed to the distractors and not to factors such as habituation or training due to the high ICC between experimental sessions.

Visual distractors have a significant effect on vergence eye movements. The stationary and dynamic distractor stimuli that generated the greatest changes compared to the control vergence eye movement without a distractor stimulus occurred when the distractor stimulus was in the opposite direction of the target stimulus. These trends were similar to those presented in previous saccadic eye movement studies with distractors. (Coëffé & O’regan, 1987; Coren & Hoenig, 1972; Kaufman & Richards, 1969). The vergence eye movements with distractor stimuli also exhibited a center of gravity (CoG) effect,

	Significance
Phase 1	
Stationary distractor	
Converging target	
BL v 1	<0.001*
BL v 2	<0.001*
BL v 3	0.002*
1 v 2	<0.001*
1 v 3	<0.001*
2 v 3	<0.001*
Diverging target	
BL v 4	0.248
BL v 5	0.001*
BL v 6	<0.001*
4 v 5	<0.001*
4 v 6	<0.001*
5 v 6	0.001*
Phase 2	
Converging target	
Diverging distractor	
BL v 13	<0.001*
BL v 14	<0.001*
BL v 15	0.183
13 v 14	0.757
13 v 15	<0.001*
14 v 15	<0.001*
Converging distractor	
BL v 16	<0.001*
BL v 17	0.253
BL v 18	0.016*
16 v 17	<0.001*
16 v 18	<0.001*
17 v 18	0.051
Diverging target	
Diverging distractor	
BL v 19	0.250
BL v 20	0.070
BL v 21	<0.001*
19 v 20	0.035*
19 v 21	0.001*
20 v 21	<0.001*
Converging distractor	
BL v 22	0.845
BL v 23	<0.001*
BL v 24	<0.001*
22 v 23	0.003*
22 v 24	<0.001*
23 v 24	0.395

Table 6. Peak velocity post hoc analysis. *Denotes statistical significance. BL = baseline eye movements.

similar to those observed within saccadic eye movements (Coëffé & O’regan, 1987; Coren & Hoenig, 1972; Kaufman & Richards, 1969). This CoG effect can be best visualized in movement type 1, where the target stimulus,

	Significance
Phase 1	
Stationary distractor	
Converging target	
BL v 1	<0.001*
BL v 2	0.001*
BL v 3	<0.001*
1 v 2	0.001*
1 v 3	<0.001*
2 v 3	<0.001*
Diverging target	
BL v 4	0.225
BL v 5	<0.001*
BL v 6	<0.001*
4 v 5	<0.001*
4 v 6	<0.001*
5 v 6	0.002*
Phase 2	
Converging target	
Diverging distractor	
BL v 13	<0.001*
BL v 14	<0.001*
BL v 15	0.036
13 v 14	0.072
13 v 15	<0.001*
14 v 15	<0.001*
Converging distractor	
BL v 16	<0.001*
BL v 17	0.886
BL v 18	0.109
16 v 17	<0.001*
16 v 18	<0.001*
17 v 18	0.042*
Diverging distractor	
Diverging distractor	
BL v 19	0.150
BL v 20	0.223
BL v 21	0.004*
19 v 20	0.612
19 v 21	0.007*
20 v 21	0.005*
Converging distractor	
BL v 22	0.218
BL v 23	<0.001*
BL v 24	0.004*
22 v 23	<0.001*
22 v 24	0.004*
23 v 24	0.734

Table 7. Response amplitude post hoc analysis. *Denotes statistical significance. BL = baseline eye movements.

and the eyes, are moving from far to near space, as the distractor stimulus is presented in the far space, as shown in Figure 7. Due to the distractor stimulus and the CoG effect, the eye movements do not attain the final vergence

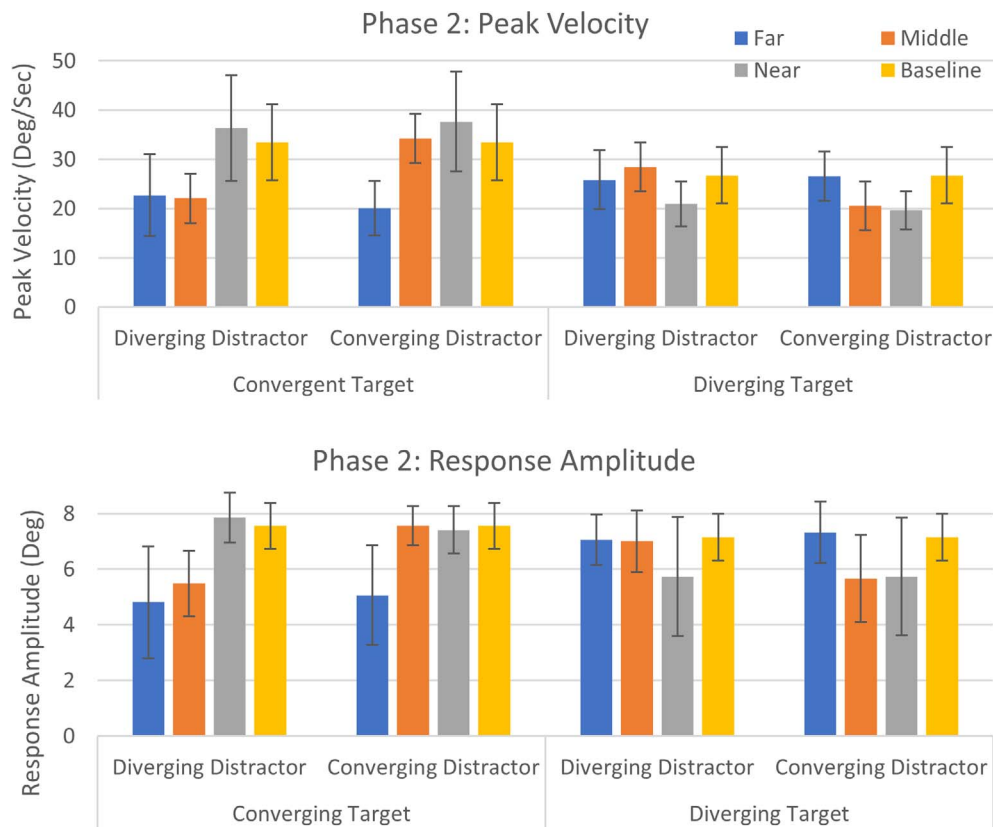


Figure 8. Phase 2 peak velocity and response amplitude where the target and distractor stimuli were dynamic (moving) and were either converging or diverging.

angle of the target stimulus. Rather, the eyes reach a final vergence angle between the location of the target and distractor stimuli. Although the subjects were instructed to maintain fixation on the X target stimulus, the subjects were not able to truly ignore the visual distractor stimulus, the O. The same trends were observed in all movements where the target and distractor stimuli were separated by greater than a vergence angular demand of 4° . This effect was quantified by the response amplitude and peak velocity. The movements that exhibited the CoG effect correspondingly had the greatest differences in response amplitude and peak velocity when compared to the control movements (with no distractors). In addition, the movements with the CoG effect showed statistically different response amplitudes and peak velocities when compared to the control movements with no distracting stimuli.

Although the CoG effect was observed in both convergent and divergent direction eye movements, there was an asymmetry dependent on stimulus direction. Even accounting for the larger peak velocities and response amplitude generated by convergent eye movements, an asymmetric trend was present. Distractors had a more significant effect on convergent compared to divergent movements. The stationary distractors show a clear indication of influence on both

convergent and divergent eye movements. However, dynamic (moving) distractors have varying degrees of effect depending on the motion and location of target stimuli. In addition to the greatest effect exhibited during the opposite directionality of the presentation of target and dynamic distractor stimuli, the convergent eye movements were also statistically different during the middle presentation of the diverging distractor stimulus when compared to the control movement with no distractor stimulus and vice versa. However, when both the target and distractor stimuli were moving in the same direction, converging or diverging, as in movement types 17 and 20, there was no statistical difference between the eye movement with the distractor and the one without. This lack of effect of the distractor on the target stimulus could be accounted to the fact that the target and distractor stimuli are making the same movement over the same angular vergence range, essentially generating a scenario where there is less competition between the target stimulus and the distractor. A CoG effect might be observed in movements 17 and 20 if the target and distractor stimuli were not overlaid on top of each other and had a different angular vergence range.

Another set of movements which exhibited no significant difference in the vergence eye movements

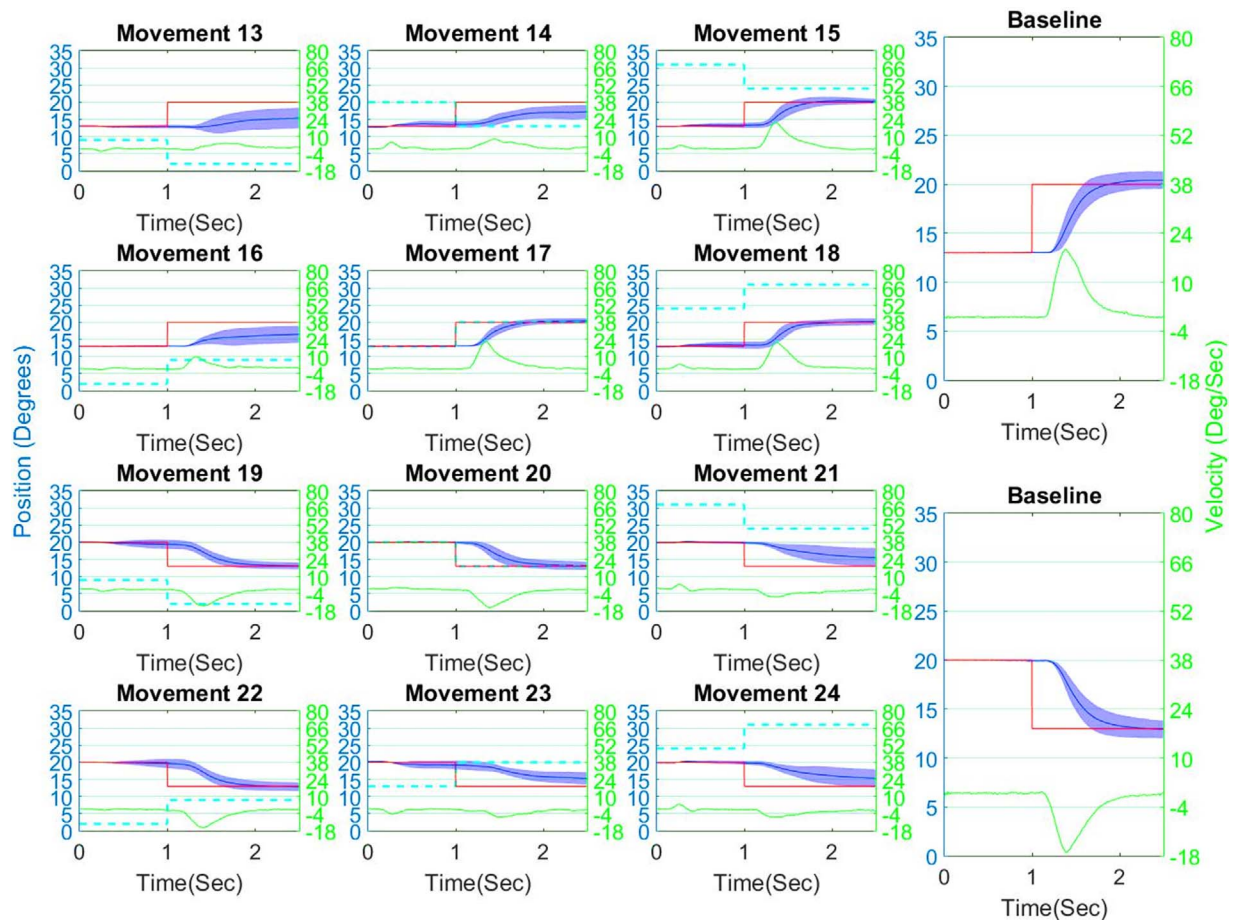


Figure 9. Phase 2 mean disconjugate movements position (solid blue line) with one standard deviation (shaded blue), peak velocity (solid green), target stimulus (solid red), and the distractor stimulus (dashed cyan).

were movement types 7 through 12 that had stationary target stimuli with converging or diverging distractor stimuli. Although there were slight deviations in the movements, these differences were not statistically significant, which illustrates how a person fixated at a particular vergence angle can maintain that fixation regardless of distractors on their midline. However, the results of this present study support that once a person starts initiating vergence eye movements, a stationary or dynamic distractor stimulus will affect those movements to a certain degree if the difference between the target and distractor stimuli is at least four degrees. Our results can also relate to other research on sustained vergence demand and attention. Prior literature studied the impact of sustained vergence angle on the ability to capture attention and report a significant connection between covert attention and sustained vergence angular demand. (Solé Puig, Pérez Zapata, Aznar-Casanova, & Supèr, 2013)

One study limitation is that we did not quantify accommodation and changes in pupil size simultaneously with disparity vergence eye movements. When a target moves in depth, the near triad is evoked, which is the integration of changes in disparity, accommo-

datory and pupillary reflex (Leigh & Zee, 2016). This study utilized a haploscope within dim lighting conditions where we presume the primary stimulus is disparity vergence since accommodation was held constant. However, we did not measure the pupil diameter or accommodation; hence, we cannot guarantee these parameters did not impact our results. Future research should include measuring eye movements, accommodation, and pupil size when possible. A second study limitation is that it is unclear what the vergence eye movement final response amplitude would be if we allowed the subject more time to fixate on the intended target. This present study concentrated on the initial transient behavior of vergence in the presence of distractors. Future study is needed to determine whether the subject would (a) improve final vergence response amplitude in the presence of distractors or (b) maintain the response amplitude described here for a longer period of time, suggesting an inability to suppress the distractor even when more time is presented to the subject.

In future studies, the methodology presented here can be used as a way to quantitatively measure distraction and indirectly quantify visual distraction in

those with binocular dysfunction. The movement types with distractors that evoke the greatest difference between control vergence movements with no distracting stimulus may be investigated in the future in patient populations who report they are easily distracted. Future directions for this methodology could include those with binocular dysfunctions such as convergence or divergence insufficiency/excess as well as patients with concussion. Those with concussion are reported to have a high incidence rate of binocular dysfunction (Alvarez et al., 2012). Vergence distractors could be used for quantification of oculomotor function.

Conclusions

The peak velocity and response amplitude of vergence eye movements were significantly different in the presence of distractors compared to vergence eye movements without distractors. A CoG effect was observed where the response amplitude of the vergence eye movements was between the target and distractor stimuli. The methodologies applied here can be used to assess visual distraction to binocular vergence eye movement in binocularly normal controls and potentially in patients with binocular dysfunctions.

Keywords: vergence, eye movements, convergence, divergence, distractors, center of gravity effect

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