Vision Research 63 (2012) 9–19

Contents lists available at SciVerse ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The frequency of horizontal saccades in near and far symmetrical disparity vergence

Eun H. Kim, Tara L. Alvarez *

Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA

ARTICLE INFO

Article history:
Received 29 November 2011
Received in revised form 27 March 2012
Available online 7 May 2012

Keywords:
Binocular vision
Version
Oculomotor
Vergence
Conjugate
Saccade

ABSTRACT

In a natural environment, saccade and vergence eye movements shift gaze in different directions and distances. In a laboratory setting, targets can be positioned precisely to elicit symmetrical vergence movements; however, saccades occur during the vergence movement even though the stimulus should not stimulate a saccadic response. These saccades may facilitate the response when the kinematics of the vergence component are modest as indicated by reduced velocities. Hence, the purpose of this study is to assess whether the frequency of saccades within vergence responses are correlated with vergence peak velocity. Ten subjects with normal binocular vision participated in this study. Eye movements were quantified using a limbus tracking system. Stimuli included 4° symmetrical convergence and divergence steps with an initial vergence angle at far (2° and 6°, respectively) and near (12° and 16°, respectively) which are known to evoke different vergence peak velocities. A saccade detecting algorithm was utilized to compute the percentage of saccades present within all vergence responses. A repeated measures ANOVA confirmed with a post hoc Bonferroni test demonstrated that convergence steps at near were slower than convergence steps at far, whereas divergence steps at far were slower than divergence steps at near in all subjects ($p < 0.02$). When the vergence peak velocity was slow, a greater number of saccades was observed. The average vergence peak velocities were inversely correlated to the number of saccades observed within the transient portion defined as after the latency to 400 ms of the movement ($r = -0.41$; $p = 0.008$), between 400 ms and 1 s of the response ($r = -0.35$; $p = 0.03$) and within the steady-state period occurring between 1 s and 3 s of the response ($r = -0.44$; $p = 0.005$). Peak velocity of vergence is dependent on the stimulus initial vergence angle. An increased prevalence of saccades was observed in vergence responses with reduced peak velocity, compared to responses with greater peak velocity. Prior research supports that saccades increase the peak velocity of vergence during combined vergence and saccadic tasks. This may in part explain the increased presence of saccades within vergence responses with reduced peak velocities. The recruitment of saccades may be utilized because of the longer period of diplopia resulting from slower vergence movements.

1. Introduction

A horizontal saccadic response is a type of version or conjugate movement that rapidly shifts the eyes in tandem. Convergence and divergence (disjunctive or vergence movements) are the inward and outward rotation of the eyes respectively, responsible for the perception of spatial depth. Under natural conditions, the visual system uses a combination of version and vergence eye movements (Busettini & Mays, 2005a, 2005b; Kumar et al., 2005; Malinov et al., 2000; Qing & Kapoula, 2004; van Leeuwen, Collewijn, & Erkelens, 1998; Zee, Fitzgibbon, & Optican, 1992). Both version and vergence movements are critical, especially when a person is engaged in tasks that utilize sustained near work such as reading or computer use. With the increased prevalence within our society of small interface devices, such as smart phones and tablets, the demand for both saccade and vergence eye movements are increasing within our daily activities. Furthermore, clinicians are reporting an increase in visual symptoms associated with sustained near work (Bababekova et al., 2011; Hoffman et al., 2008; Howarth, 2011); yet, only a few studies have investigated the etiology of these symptoms (Collier & Rosenfield, 2011; Ishikawa, 1990; Rosenfield, 2011). This study quantifies the frequency of horizontal saccades in symmetrical vergence eye movements that are prevalent in both near and far visual tasks.

Convergence typically occurs with other eye movements. However, it is possible to elicit a pure disparity vergence stimulus by precisely positioning visual targets along the subject's midline. Our laboratory and other investigators have published that even when symmetrical vergence stimuli are presented to a subject, many of the responses contain horizontal saccades (Coubard & Kapoula, 2008; Semmlow et al., 2008, 2009). Coubard and Kapoula (2008) characterized saccades during symmetrical 8.2° convergence steps and 6.2° divergence steps with an initial vergence

* Corresponding author. Fax: +1 973 596 5222.
E-mail address: tara.l.alvarez@njit.edu (T.L. Alvarez).

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http://dx.doi.org/10.1016/j.visres.2012.04.013

angle of 8.5°. They reported that saccades were found in up to 84% of the vergence responses and identified six morphologies of the saccadic components. Ying and Zee (2006) reported differences in the timing and amplitude of the saccades within divergence movements after short and long periods of sustained symmetrical convergence (Ying & Zee, 2006). Semmlow and colleagues et al. (2008) demonstrated that the initial saccades occurred in a preferred direction (leftward or rightward) during 4° symmetrical vergence responses (Semmlow et al., 2008). These investigators concluded that horizontal saccades in symmetrical vergence tend to quickly bring one eye closer to the target since saccadic peak velocities are typically an order of magnitude faster than vergence peak velocities (Coubard & Kapoula, 2008; Semmlow et al., 2008, 2009; Ying & Zee, 2006). Furthermore, as the aforementioned studies report, saccades are commonly observed in symmetrical vergence when the visual input does not directly stimulate a conjugate response.

The speed of vergence has an impact on a person's activities of daily living. For example, one study on repetitive vergence movements, analogous to performing visual tasks for a prolonged period of time, reports an average reduction of 20% in vergence peak velocity (comparing the responses from the beginning to those recorded at the end of the session) (Yuan & Semmlow, 2000). In addition, quantitative studies have reported that convergence peak velocity is significantly reduced compared to age matched controls when a person has a vergence dysfunction known as convergence insufficiency (Alvarez et al., 2010; Thiagarajan, Ciuffreda, & Ludlam, 2011). None of these studies conducted a systematic investigation of the relationship between the vergence peak velocity and the prevalence of saccades commonly observed within symmetrical vergence responses. We propose that conducting this analysis will yield insight into how the vergence system may compensate for slow velocity movements. This is relevant because the vergence peak velocity can be significantly reduced as a result of fatigue and/or vergence dysfunction (Alvarez et al., 2010; Yuan & Semmlow, 2000).

Studies have not yet investigated the prevalence of saccades within responses to symmetrical vergence stimuli located at different initial vergence angles (near versus far) to analyze whether a correlation exists between the speed of the vergence movement and the number of saccades generated within the response. Thus, the purpose of the current study is to investigate whether the frequency of saccades during symmetrical vergence movements is dependent on vergence peak velocities. A within-subject design can be engineered to elicit vergence responses with different peak velocities. Both models and empirical data support that divergence responses at far will be slower than divergence responses at near, and convergence responses at near will be slower than those at far (Kim et al., 2010, 2011; Lee et al., 2009; Patel, Jiang, & Ogmen, 2001; Patel et al., 1997). By employing a within-subject experimental design using the four vergence step stimuli (convergence and divergence steps at near and far initial vergence angles), we will test our hypothesis that responses with slower vergence peak velocities will contain a greater number of saccades compared to those that have faster kinematics.

2. Methods

2.1. Subjects

Ten subjects (5 males, 5 females) without a history of brain dysfunction or injury participated in this study. Subjects were between 20 and 31 years of age with a mean and standard deviation of 22.9 ± 3.1 years. All subjects had an NPC less than 6 cm and normal binocular vision defined as better than 50 s of arc assessed by the Randot Stereopsis Test (Bernell Corp., South Bend, IN, USA) using methods described in detail in our previous research (Alvarez et al., 2010). All subjects were emmetropes except for subjects S1 and S9 who were myopes (1.75 ± 0.71 D) and were corrected for refractive error during the experiment. This study was approved by the New Jersey Institute of Technology Institute Review Board in accordance with the Declaration of Helsinki prior to the experiment. All subjects gave informed written consent.

2.2. Measurement of eye movements and visual stimuli

Eye movements were recorded using an infrared (λ = 950 nm) system manufactured by Skalar Iris (Model 6500, Netherlands). The eye movement responses were within the linear range of the system (±25°). Visual stimuli were displayed using a haploscope where two computer screens were used to generate a symmetrical (identical in shape, light intensity and color) disparity vergence stimulus along the subject's midline. The stimulus, a green vertical line 2 cm in height and 2 mm in width, was presented on a black background. Two partially reflecting mirrors projected the two vertical lines from the computer screens into the subject's line of sight. The stimuli from the computer screens were adjusted with the mirrors to calibrate the visual stimulus with real targets located at measured distances from the subject's midline prior to data collection. An inter-pupillary distance of 6 cm was assumed. The stimuli monitors were placed 40 cm away from the subject, hence the accommodative stimulus was held constant. During the experiment, only the visual stimulus displayed on the computer screen was seen by the subject. The subject's head was restrained using a custom chin rest to eliminate head movement and avoid any vestibular influences during the experiment.

The left-eye and right-eye responses were recorded, calibrated, and saved separately for offline data analysis. Digitization of eye movement data were performed using a 12-bit digital acquisition (DAQ) hardware card with a range of ±5 V (National Instruments 6024 E series, Austin, TX, USA). The entire system was controlled by a custom LabVIEW™ 8.0 program (National Instrument, Austin, TX, USA) which generated the visual stimuli and digitized the eye movement data sampling at a rate of 200 Hz (Guo, Kim, & Alvarez, 2011).

2.3. Experimental protocol

The vergence step stimuli were near convergence steps (12° initial vergence angle), far convergence steps (2° initial vergence angle), near divergence steps (16° initial vergence angle) and far divergence steps (6° initial vergence angle). The vergence step stimuli were randomly intermixed and presented after a random delay between 0.5 and 2.0 s to avoid prediction which is known to enhance vergence peak velocities (Alvarez et al., 2005, 2002). Due to the randomization algorithm, approximately 25–30 responses of each stimulus were collected for data analysis. At a minimum, 25 responses were collected of each stimulus type.

2.4. Data analysis

Vergence data were calibrated using two-points, the initial and final vergence position demand of the vergence step stimuli similar to our past study (Kim et al., 2010). Our system has a high degree of linearity, within 3% between ±25° horizontally (Horng et al., 1998). Vergence was calculated by subtracting the right-eye response from the left-eye response to yield a net vergence response. Conjugate or version was calculated by averaging the right-eye response and the left-eye response. Vergence and conjugate velocity traces were computed using a two-point central difference algorithm (Bahill, Kallman, & Lieberman, 1982). Convergence responses were plotted as positive while divergence responses were plotted as negative.