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Quantifying interactions between accommodation and vergence in a binocularly normal population

Laura E. Sweeney *, Dirk Seidel, Mhairi Day, Lyle S. Gray

Department of Vision Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow, Scotland G4 0BA, United Kingdom

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ABSTRACT

Stimulation of the accommodation system results in a response in the vergence system via accommodative vergence cross-link interactions, and stimulation of the vergence system results in an accommodation response via vergence accommodation cross-link interactions. Cross-link interactions are necessary in order to ensure simultaneous responses in the accommodation and vergence systems. The crosslink interactions are represented most comprehensively by the response AC/A (accommodative vergence) and CA/C (vergence accommodation) ratios, although the stimulus AC/A ratio is measured clinically, and the stimulus CA/C ratio is seldom measured in clinical practice. The present study aims to quantify both stimulus and response AC/A and CA/C ratios in a binocularly normal population, and determine the relationship between them. 25 Subjects (mean ± SD age 21.0 ± 1.9 years) were recruited from the university population. A significant linear relationship was found between the stimulus and response ratios, for both AC/A ($r^2 = 0.96$, $p < 0.001$) and CA/C ratios ($r^2 = 0.40$, $p < 0.05$). Good agreement was found between the stimulus and response AC/A ratios (95% CI −0.06 to 0.24 MA/D). Stimulus and response CA/C ratios are linearly related. Stimulus CA/C ratios were higher than response ratios at low values, and lower than response ratios at high values (95% CI −0.46 to 0.42 D/MA). Agreement between stimulus and response CA/C ratios is poorer than that found for AC/A ratios due to increased variability in vergence responses when viewing the Gaussian blurred target. This study has shown that more work is needed to refine the methodology of CA/C ratio measurement.

1. Introduction

During normal binocular vision the accommodation and vergence systems act simultaneously to provide clear bifoveal retinal images which are then unified in the visual cortex to form a single binocular image. The primary stimuli for accommodation and vergence are image blur (Fincham, 1951) and horizontal binocular disparity (Wheatstone, 1838) respectively. The accommodation and vergence systems are coupled to ensure a coordinated near response. These interactive components are quantified by the AC/A and CA/C ratios respectively (Fincham & Walton, 1957), and ensure that accommodation responses are accompanied by simultaneous vergence eye movements and vice versa, thereby maintaining clear, single vision of objects at all distances (Schor & Kotulak, 1986).

Accommodation and vergence responses are modeled as negative feedback control systems using control systems theory (Campbell & Westheimer, 1960; Schor & Kotulak, 1986; Stark, Takahashi, & Zames, 1965; Toates, 1970, 1974). One of the most widely accepted models includes phasic (fast acting) and tonic (slow acting) components, and components representing the interactions between the two systems (Schor & Kotulak, 1986). Schor and Kotulak (1986) presented experimental evidence placing the cross-link interactions after the phasic components of the systems, but before the tonic components (Schor & Kotulak, 1986). Stimulation of the accommodative vergence cross-link resulted in changes in the tonic vergence component and stimulation of the vergence accommodation cross-link resulted in changes in the tonic accommodation component (Schor & Kotulak, 1986) (Fig. 1). The positioning of the cross-links in Schor and Kotulak's model (1986) would mean that vergence adaptation would reduce output of the vergence accommodation cross-link and accommodation adaptation reduces the output of the accommodative vergence cross-link without changing the gain of either cross-link component (Schor & Tsuetaki, 1987). The cross-link components are considered by some to be a fixed characteristic of the oculomotor system (Schor & Kotulak, 1986), which remains stable over time (Bruce, Atchison, & Bhoola, 1995; Rainey et al., 1998). Other studies have

* Corresponding author.
E-mail addresses: Laura.Sweeney@gcu.ac.uk (L.E. Sweeney), D.Seidel@gcu.ac.uk (D. Seidel), M.Day@gcu.ac.uk (M. Day), L.S.Gray@gcu.ac.uk (L.S. Gray).

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found that the cross-link ratios can be altered temporarily (Eadie et al., 2000; Judge & Miles, 1985; Schor & Horner, 1989), and this has been attributed to changes in the output of the slow tonic components (Fisher & Ciuffreda, 1990; Schor & Horner, 1989). Some models have found the cross-links are reciprocally related (i.e. the AC/A is equal to 1/CA/C) (Schor & Kotulak, 1986; Schor, 1992), although other studies have been unable to replicate this finding (Bruce, Atchison, & Bhoola, 1995; Owens, 1980; Owens & Wolf-Kelly, 1987; Rosenfield, Ciuffreda, & Chen, 1995; Semmlow & Hung, 1981). Other models suggest the cross-links are inversely related (i.e. as the AC/A increases in value the CA/C ratio decreases) (Semmlow & Hung, 1981).

Previous work has shown that patients with binocular vision anomalies often have abnormal AC/A and CA/C ratios (Lara et al., 2001; Porcar & Martinez-Palomera, 1997; Von Noorden, 1996). Abnormal AC/A and CA/C ratios are important diagnostic criteria for both convergence excess and convergence insufficiency (Lara et al., 2001; Porcar & Martinez-Palomera, 1997). It has also been found that patients with convergence excess and convergence insufficiency often exhibit unequal adaptation of vergence and accommodation, which may be the cause of the abnormal AC/A and CA/C ratios (Schor, 1988). Convergence insufficiency patients often exhibit a low AC/A ratio (Daum, 1984), hence if the AC/A and CA/C ratios are reciprocally related, it would be expected that convergence insufficiency patients will have high CA/C ratios (Schor & Horner, 1989), however due to methodological difficulties few studies have examined this possibility (Brautaset & Jennings, 2006). The AC/A ratio has also been used as a predictive measure of treatment outcomes (Daum, 1984; Kim et al., 2012). It has been shown that, within a group of convergence insufficiency patients, a lower AC/A ratio decreased the probability of successful orthoptic treatment (Daum, 1984). It has also been shown that normalization of the AC/A ratio in non-refractive accommodative esotropia patients (using bifocals) can be used as a predictor of the success of treatment (Kim et al., 2012).

Clinical assessment of the CA/C ratio is clearly an important measure of binocular function, but is rarely undertaken because of methodological difficulties in opening the accommodation loop while measuring vergence eye position precisely (Rosenfield, 2009). Open loop responses are responses unregulated by feedback, closed loop responses are regulated by feedback. In order to gain a fuller understanding of the cross-link interactions both ratios should be assessed clinically. This will become increasingly important as the use of stereoscopic displays increases because studies have shown that unequal accommodation and vergence demands found in 3D displays can temporarily modify the cross-link interactions (Eadie et al., 2000; Miles, Judge, & Optican, 1987). It has been suggested that changes in the cross-link interactions could be responsible for asthenopic symptoms (Hoffman et al., 2008), although the cause of asthenopia experienced while viewing 3D displays has yet to be determined (Howarth, 2011; Kooi & Toet, 2004; Speranza et al., 2006).

The stimulus CA/C ratio compares the vergence accommodation response to the vergence stimulus at each stimulus level. The response CA/C ratio compares the vergence accommodation response to the vergence response at each stimulus level. The response CA/C ratio provides the most accurate measure of this cross-link interaction as the responses of both the accommodation and vergence systems are observed directly (Tsuetaki & Schor, 1987). Of the studies which have examined either the stimulus or the response CA/C ratio in adult populations (Bruce, Atchison, & Bhoola, 1995; Hung, Cuiffreda, & Semmlow, 1986; Rosenfield, Ciuffreda, & Chen, 1995; Tsuetaki & Schor, 1987; Wick & Currie, 1991), only one has compared stimulus and response ratios (Tsuetaki & Schor, 1987). Tsuetaki and Schor (1987) reported good agreement between the stimulus and response CA/C in a small sample of 6 subjects. The accommodation loop was opened using a difference of Gaussian target and the authors suggested this method could be employed to measure the stimulus CA/C in clinical practice (Tsuetaki & Schor, 1987). Other studies have examined only the response CA/C ratio (Bruce, Atchison, & Bhoola, 1995; Hung, Cuiffreda, & Semmlow, 1986; Rosenfield, Ciuffreda, & Chen, 1995) and further work is required to establish the characteristics of the relationship between stimulus and response CA/C ratio in a larger sample.

Many studies which have investigated the CA/C ratio previously have used a difference of Gaussian target (Brautaset & Jennings, 2006; Eadie et al., 2000; Tsuetaki & Schor, 1987; Wick & Currie, 1991). The low spatial frequency characteristics of the difference of Gaussian target allows stimulation of the vergence system while the accommodation loop remains open (Tsuetaki & Schor, 1987). Previous investigations have shown that the accuracy of steady state fixation depends on the spatial and temporal properties of the stimulus (Schor & Tyler, 1981). Schor and Tyler (1981) showed that the size of Panum's fusional area can range from approximately 2.5 arcmin for targets high in spatial and temporal frequency (2 cpd/5 Hz) to >20 arcmin for targets low in spatial and temporal frequency (0.125 cpd/0.1 Hz), suggesting that vergence responses to low spatial frequency targets (such as difference of Gaussian targets) will be inherently more noisy due to the stimulus characteristics.

The stimulus AC/A ratio compares the accommodative vergence response to the accommodation stimulus at each stimulus level, whereas the response AC/A ratio measures the accommodative vergence response and compares it to the accommodation response at each stimulus level. Clinically the stimulus AC/A ratio is easily obtained, and shows good agreement with response measures of the AC/A ratio (Alpern, 1962; Rainey et al., 1998). The response AC/A ratio provides the most accurate measure of the strength of the interaction between the two systems. Measurement of the response AC/A ratio is time consuming and requires specialist equipment and is rarely undertaken in a clinical setting, therefore a robust clinical measure of the stimulus AC/A ratio is essential as part of a comprehensive assessment of binocular

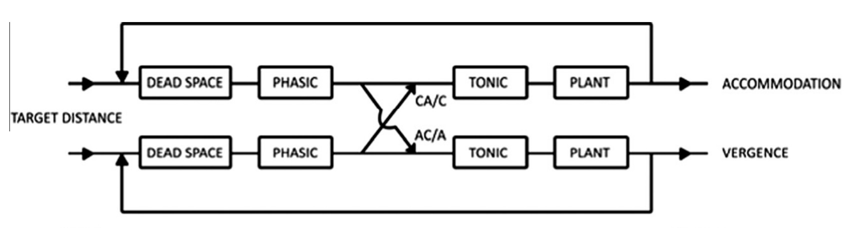

Fig. 1. Negative feedback model of the accommodation and vergence system. Phasic, tonic and interactive components of the accommodation and vergence responses are all represented (after Schor & Kotulak, 1986). The Dead space represents depth of focus and Panum's fusional area in the accommodation and vergence systems respectively. The phasic components represent the initial fast component of response of the accommodation and vergence systems. The tonic components represent the sustained response of the accommodation and vergence systems. The plant represents the physiological components of the accommodation and vergence systems.