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Stabilization of gaze: A relationship between ciliary muscle contraction and trapezius muscle activity

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ABSTRACT

In an experimental study four levels of oculomotor load were induced binocularly. Trapezius muscle activity was measured with bipolar surface electromyography and normalized to a submaximal contraction. Twenty-eight subjects with a mean age of 29 (range 19–42, std 8) viewed a high-contrast fixation target for four 5-min periods through: (i) −3.5 dioptre (D) lenses; (ii) 0 D lenses; (iii) individually adjusted prism D lenses (1–2 D base out); and (iv) +3.5 D lenses. The target was placed close to the individual's age-appropriate near point of accommodation in conditions (i–iii) and at 3 m in condition (iv). Each subject's ability to compensate for the added blur was extracted via infrared photorefraction measurements. A bitwise linear regression model was fitted on group level with eye-lens refraction on the *x*-axis and normalized trapezius muscle EMG (%RVE) on the *y*-axis. The model had a constant level of trapezius muscle activity – where subjects had not compensated for the incurred defocus by a change in eye-lens accommodation – and a slope, where the subjects had compensated. The slope coefficient was significantly positive in the −D (i) and the +D blur conditions (iv). During no blur (ii) and prism blur (iii) there were no signs of relationships. Nor was there any sign of relationship between the convergence response and trapezius muscle EMG in any of the experimental conditions. The results appear directly attributable to an engagement of the eye-lens accommodative system and most likely reflect sensorimotor processing along its reflex arc for the purpose of achieving stabilization of gaze.

1. Introduction

The point of departure for the present study is the notion that accommodative/vergence eye movements are intrinsically integrated with head and scapular area muscle functionality. This since visual targets 1° or further away from the fovea constitutes inadequate sensory stimuli to elicit or drive a well functioning accommodative response (Campbell, 1954; Gu & Legge, 1987). Campbell (1954) concluded that the receptors involved in the accommodation reflex are the foveal cones and that in the absence of a foveal stimulus the accommodative reflex is not fully elicited. Functional (hard-wired) neck/scapular muscle area action, in order to stabilize the retinal images, may accordingly be a natural consequence of oculomotor processing needs at near or far distances. The unrestrained head shows considerable motion during naturalistic viewing conditions, even when attempts are made to keep it as still as possible. Active image stabilization by neck/scapular area effectors may therefore serve to minimize the occurrence of unwarranted extra foveal stimulation. Hence, a neural command to sharply fixate a target at near (e.g., an alphanumerical character) during static, strenuous and/or fatiguing accommodative/vergence viewing conditions may functionally impact on neck/scapular area muscles functioning by increasing the mechanical load and by reducing the load variation, in order to stabilize gaze (Lie & Watten, 1987; Richter, Andersson, Schneider, & Långström, 2005; Simons, 1943). Illumination of the sensorimotor events underlying sustained accommodation/vergence eye movements at near during steady-state foveal fixation complements and extends ongoing scientific research concerning behavior and neural mechanisms underlying eye–neck/scapular area functionality.

Richter et al. (2005) extended earlier knowledge regarding central mechanisms underlying gaze stabilization by illuminating via

Abbreviations: D, dioptre; Fixation, sustained steady-state active foveal fixation/accommodation/vergence on a high-contrast target; *Neg-Near*, reduction of optical blur by plus accommodation/vergence in response to concave −3.50 D lenses placed in front of both eyes; *Neutral-Near*, a no-blur reference viewing condition; *Pos-Far*, attempts at voluntary reduction of optical blur by negative accommodation/vergence in response to convex +3.50 D lenses placed in front of both eyes; *Prism-Out*, reduction of optical blur by convergence eye movements in response to a set of prism lenses (1–2 D base out on each eye).

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brain imaging (positron emission tomography, PET) the cortical events underlying eye-lens accommodation. Both the primary motor cortex and the somatosensory cortex showed reduced blood flow during ongoing so called negative accommodation responses (Hofstetter, Griffin, Berman, & Everson, 2000) at somatotopic coordinates that implicated the neck and the shoulder area (Richter et al., 2005). A supplementary observation was that the frontal regional cerebral blood flow (rCBF) decreases observed in two previous studies (Richter, Lee, & Pardo, 2000; Richter et al., 2005) have little to do with the direction of the accommodative/vergence response (i.e. with increases in eye-lens accommodation/vergence or inhibition thereof). In both cases an ocular stabilization process seems to have been triggered to ensure that the target is held in the retinal area of highest visual acuity. Hence, although a close functional relationship between oculomotor load and activation of the neck and scapular muscles does seem realistic, the mechanism(s) coupling the two systems to one another has/have rarely been formally tested. The purpose of the present study was accordingly to follow up the results of the few previous studies and test the proposition that sustained periods of accommodation/vergence load, in response to near work fatigue, trigger musculoskeletal activation in the neck–scapular area. The specific objectives were to test the hypothesis that brief periods of accommodation/vergence load increase the muscular activity in the upper trapezius muscle, with more contraction of the ciliary/extraocular muscles leading to increased trapezius activity.

2. Material and methods

2.1. Subjects

Twenty-eight subjects (18 females and 10 males), naïve and unpractised participants, with a mean age of 29 (range 19–42, std 8) were included in the study. As individuals afflicted by chronic work-related myalgia and/or professional oculomotor near-work problems (i.e. asthenopia) may react in different ways to the present experimental conditions (Strøm, Røe, & Knardahl, 2009; Treaster, Marras, Burr, Sheedy, & Hart, 2006; Wiholm, Richter, Mathiassen, & Toomingas, 2007) two different categories of subjects were included in the current study: healthy symptom-free subjects and subjects with a history of eye disorder and neck disabilities. Fifteen of the subjects (mean age 27, range 19–42, std 8) were healthy and thirteen had a history of eye disorder (asthenopia) and non-specific neck disorders (mean age 32, range 21–42, std 7). The patient group had been referred by general doctors or optometrists to an orthoptist for further investigation and treatment. All asthenopic participants but one were classified as neck disabled on the basis of the Neck Disability Index (MacDermid et al., 2009; Vernon & Mior, 1991). The subjects' orthoptic treatment had been completed 2–3 months prior to their participation in the present study. The study followed ethical committee guidelines and informed consent was given by each subject before participation in this study. The study was approved by the Uppsala University Medical Ethical Review Board.

2.2. Eye exam

To prevent inclusion of eye disease all symptom-free participants went through an optometric examination, which included standardized measures of acuity, motility stereopsis, retinal correspondence and fusion. All subjects in the control group had a normal unaided or aided acuity with no history of eye disease. The near points for both accommodation and convergence functions were normal, as was motility. The difference between habitual correction and the retinoscopically measured refractive errors was negligible (<0.5 dioptres) in all cases. Pupil size and stereopsis at near and far distances were also normal.

The asthenopic subjects were subjected to an orthoptic and ophthalmological examination, starting with a general medical history. Visual acuity was tested for distance (5 m) and near (40 cm), with the KM acuity test (Moutakis, Stigmar, & Hall-Lindberg, 2004) uncorrected and with best optical correction. A complete refraction in cycloplegia using an autorefractometer was done in asthenopic subjects. For cycloplegia a mixture of cyclopentolate 0.75% and phenylephrine 2.5% was used. Hyperopia $\geqslant$ +0.50 D, myopia $\leqslant -0.5$ and astigmatism a $\leqslant -0.5$ were defined as refractive errors. Binocular vision was assessed with the Lang II stereo test and with the Bagolini striated glass test for distance and near. Strabismus was determined using the cover test for distance and near with the best correction. A prism cover test was used to assess the angle of strabismus. The near point of convergence and accommodation was measured with the Royal Air Force (RAF) rule.

All significant refractive errors were corrected for by spherical and cylindrical glasses. The asthenopia was of a mixed origin, ranging from uncorrected refractive errors (hypermetropia, myopia, astigmatism and anisometropia) to neuromuscular anomalies (muscular asthenopia) such as heterophoria, heterotropia and convergence insufficiency. Nine asthenopic subjects with accommodative insufficiency and accommodative excess were helped with appropriate convex glasses for close range and computer distance. Two subjects with accommodative insufficiency combined with convergence insufficiency were prescribed convex glasses and prism glasses (+1.0 and 3 prism D). Only one subject was given prism glasses without any spherical addition for near work.

2.3. Optometric recordings

The accommodative/vergence response was assessed using an infrared autorefractor (PowerRefractor R 03, Plusoptix, Nurnberg, Germany) based on the principles of photorefraction (Blade & Candy, 2006; Wolffsohn, Hunt, & Gilmartin, 2002). The photorefraction technique analyzes the vergence of rays that are returned from the eye after reflecting an illuminated spot on the retina. In brief, the slopes of the brightening distribution in the pupil are converted to a refractive error. The range of measurements extends from about −8.0 D to +6.0 D, depending on pupil size in both eyes at the same time, and the direction of the pupil axes (Blade & Candy, 2006). Because fixation is monitored continuously, changes in refraction due to off-axis refractive errors (e.g., as due to spherical aberration) rather than eye-lens accommodation can be excluded. One limitation is that small pupils (which return to little light) cannot be measured (Wolffsohn et al., 2002). The optometer operates with a minimum pupil of 2.8 mm and tolerates eye movements ±25° from a central fixation. The infrared autorefractor records spherical refraction at 25 Hz without compensation for the working distance, i.e. an emmetropic or corrected eye focused at the plane of the autorefractor at 1 m will register 0 D of sphere. According to the manufacturer, the precision of measurements is ±0.25 D.

The optometer was calibrated by instructing observers to binocularly fixate a high-contrast LED target placed at 1 m viewing distance through a series of spherical plus and minus lenses (from −8.0 to +8.0 D), to lock fixation on the target and to continue to do so despite the presence of blur and/or diplopia (cf. Richter, Crenshaw, & Lyskov, 2007). The eye-lens refraction values resulting from this procedure were observed to change linearly with the power of the range of added trial lens blur. The linear regressions performed on each individual's data confirmed that the slopes were close to one, that the *y*-intercepts approached zero and that the fitted line accounted for nearly all of the observed variance in the individual refractive measurements (cf. Blade & Candy, 2006). Outside the linear range the response curve flattened out and the values were no longer related to the magnitude of the power of the trial lens added. The ability of the optometer to detect refractive errors during unaided fixation on the same target was examined by comparing its output to measurements obtained in parallel via a Topcon KR-8100 autorefractor (Topcon Medical System, Inc.). The individual refraction values obtained from the two optometers were found to be in excellent agreement with one another (cf. Allen, Radhakrishnan, & O'Leary, 2003; Hunt, Wolffsohn, & Gilmartin, 2003). Thus, the optometer used in the current study provided satisfactory absolute and relative measurements of defocus blur.

In addition to the measuring the eye's dioptric focus, the optometer measures the convergence response, extracted via recordings of the horizontal displacements of the interpolated centre of the corneal Purkinje images. The Purkinje displacements may be converted into convergence angles using the Hirschberg ratio. The individual convergence response obtained in this way was calibrated in the present study by having the subjects posture their accommodative/convergence response on a near-far high-contrast fixation target which was stepped between 0.33 D (3 m) and the individually determined near point during 15 successive stimulus presentations. The fixed offset, which was observed between stimulus and response dioptres, indicated that it was appropriate to apply an individual scale factor to correct for a linear measurement error.

2.4. Electromyography and electrocardiography

Electromyography (EMG) was collected bilaterally from the descending part of the upper trapezius muscle. The skin was cleansed with alcohol and rubbed with a fine cloth. Two disposable Ag–AgCl electrodes were placed along the direction of the muscle fibers with a centre-to-centre distance of 2 cm. The electrodes were centred 2 cm lateral of the mid-point of the line connecting vertebra C7 and acromion (Mathiassen, Winkel, & Hägg, 1995). Electrocardiography (ECG) was recorded to facilitate filtering of heart signal disturbances in the EMG signals.

The EMG and ECG signals were amplified, band-pass filtered (30–3000 Hz) and sampled at 2000 Hz (EMG100C, BIOPAC Systems, Inc., Santa Barbara, CA, USA). The EMG data were normalized to the root-mean-square (RMS) value of the middle 10 s of 15-s submaximal contractions (the reference voluntary electrical activity; RVE). During the reference contractions both arms were straight and horizontal in abduction (Mathiassen et al., 1995), which corresponds to 15–20% of a maximal voluntary contraction. The mean value of three repeated RVE contractions was used to normalize and express the measurement data in %RVE. The EMG recordings were RMS-converted in 100-ms windows and quadratically adjusted for noise (the lowest 400-ms moving RMS value of a recording during relaxation). The 50th percentiles of each session's RMS values were chosen as an indicator of muscular activity level.

To identify the timings of the QRS peaks in the ECG the signal was down-sampled to 1000 Hz and high-pass filtered using a third-order Butterworth filter with a cut-off frequency of 4 Hz. The signal was then divided into 2-s windows and the lowest, maximum value from these periods was identified, of which 0.78 of that value was used as a threshold in identifying the *R*-peaks. When two or more 'peaks' reached above the threshold within a time period of 200 ms, only the highest one was kept. When *R*–*R* intervals were shorter than 0.7 times the median interval, the latter of the two peaks were seen as an ectopic beat, which was omitted and replaced by a new *R*-peak, the time of which was calculated by using cubic spline interpolation (Lippman, Stein, & Lerman, 1994). All ECG plots, *R*-peak identifications and ectopy corrections were visually inspected. The quality of the ECG signal was high and no unidentified *R*-peaks were seen. For all subjects and all sessions, only three false, noise-induced peak identifications were seen; these were deleted before further analyses. The raw EMG signals were often disturbed by additive heart signals. This disturbance was eliminated by subtracting the estimated timings of the *R*-peaks from the EMG signals.

2.5. Procedure

Throughout the study participants were seated in an office chair in a slightly leaning-back posture supported by a combined head and backrest adjusted to their morphology. The subject's upper arms were alongside the trunk. Their hands were stationary and resting, either on their lap or on adjusted armrests. Because the eyes had to be aligned to the axis of the optometer, movements from the neck/scapular area were not allowed. The high-contrast fixation target consisted of a bright × illuminated from behind with a polychromatic LED (Light Emitting Diode, LED) (Everlight Electronics Co., Ltd., England) which emitted a white color. This target was positioned in front of the subject and in the midsagital plane. The fixation point stimuli subtended 1.3° at a 22.2 cm (4.5 D) viewing distance. The physical size of the target at the 3 m (0.33 D) viewing distance was scaled to approximate the same visual angle. Defocus blur was introduced into the optical axis of the viewing eyes via lenses that were mounted in trial frames (Oculus Inc., Dutenhofen, Germany). The subjects were asked to compensate for the incurred blur by reflexively or voluntarily adjusting the dioptric strength of their crystalline eye-lens. Prior to participation in the experiment, the subjects' unaided eyes were subjected to an autorefractor examination. Any detected ammetropias were corrected for in the experiment to insure that the level of defocus blur (stimulus dioptres) was task-appropriate and similar for all participants.

The baseline (eyes closed rest), which preceded each experimental session, had a duration of 3 min. The participants performed four viewing tasks, which involved 5 min of steady-state foveal fixation upon the LED. A partial Latin square was used to counterbalance potential order effects across participants. The participants focused continuously on the target through: (i) −3.5 D lenses (*Neg-Near*); (ii) 0 D lenses (*Neutral-Near*); (iii) individually adjusted prism D lenses (1–2 D base out on each eye) (*Prism-Out*); or (iv) +3.5 D lenses (*Pos-Far*). The fixation target was generally placed 5 D away from the age-appropriate near point of accommodation in conditions (i–iii) and at distance (3 m, 0.33 D) in condition (iv). The expected amplitude of accommodation by age (in years) was calculated using Hofstetter's (1950) equation:

$$\text{Expected amplitude of accommodation} = 100/(18.5 - (0.3 \times \text{age})) \quad (1)$$

Placement of the near LED in the case of a 30-year-old subject (expected near point at 9.5 cm or 10.5 D) was accordingly calculated to be 22.2 cm (4.5 D). This stimulus set-up was chosen to avoid unduly large response magnitudes which would render the pupil size to be insufficiently small, leading to data loss. See Fig. 1.

The *Neutral-Near* condition, a congruent accommodation/vergence stimulus condition, served as a neutral reference. It should be borne in mind however that under the present stimulus conditions it cannot be assumed *a priori* that a single fixation point can be used to precisely position the focal point onto the target (Johnson, 1976). The viewing conditions were in many ways non-optimal (i.e. the room was dark, the accommodative stimuli were relatively close and the accommodation/vergence stimulation was continuous, with no rest or variation involved). However the present aim was to compare trapezius muscle activity with the

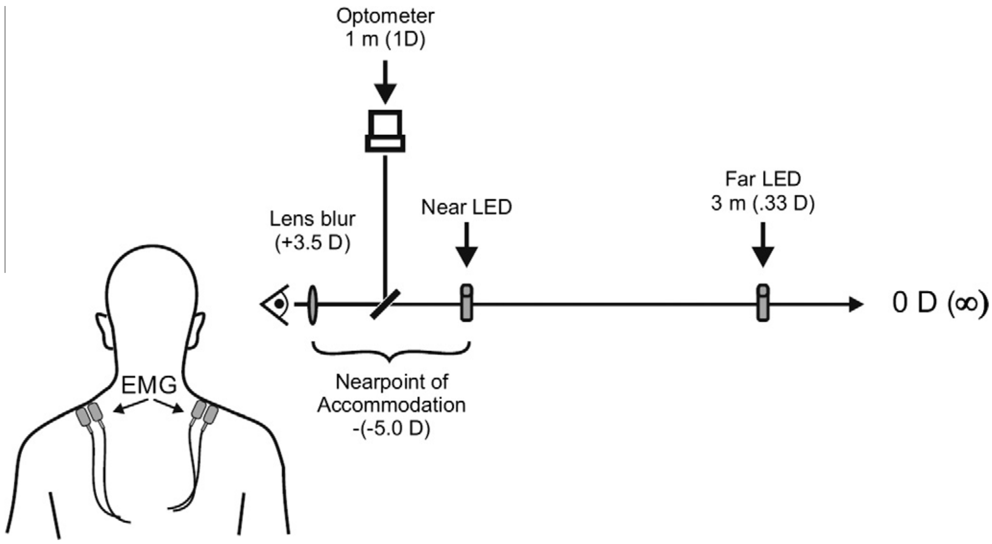

Fig. 1. The experimental set-up. The near high-contrast stimulus was placed close to the age-appropriate near point of accommodation. The far stimulus was placed at 3 m (0.33 D). Objective measures of compensatory accommodative/vergence changes of the eye-lens, to 'nullify' the effect of the trial lens, were obtained by the infrared optometric recordings. The trapezius muscle activity was measured with bipolar surface electromyography (EMG).

degree of accommodation/vergence, not necessarily with the precision of an absolute value of accommodation.

The non-congruent accommodation/vergence stimulus condition *Neg-Near* required the subjects to maintain maximal focus on the target when the −3.5 D lens interrupted their line of sight while maintaining convergent visual axes on the LED target. Successful accommodation/vergence performance under these circumstances requires sustained contraction of the ciliary muscle to overcome the minus dioptric blur (cf. Richter et al., 2000). Earlier experimental work indicates increased trapezius muscle EMG activity under such stimulus conditions (Lie & Watten, 1987).

The *Prism-Out* condition required the subjects to maintain convergent visual axis when prism lenses (each 1–2 D, base out) interrupted the lines of sight. Fusional convergence eye movements are necessary under such incongruent stimulus conditions in order to re-enter the images onto the foveas again. In this condition the load imposed on the ciliary muscle is unchanged (i.e. similar to *Neutral-Near*). Hence this condition allows relatively more load to be imposed on the extraocular muscles (although some subjects might also respond with accommodative convergence). Discrepancies between accommodative and vergence stimuli in the retinal image have been attributed to work-related visual fatigue (Ukai & Howarth, 2008). In the clinic this type of heterophoria is also associated with musculoskeletal pain and discomfort (Borsting et al., 2003; Sucher, 1994).

The *Pos-Far* condition, which involved attempting to maintain fixation on a 3 m (0.33 D) distant target while +3.5 D lenses were placed in front of the eyes, derives from Richter et al. (2005). The amount of stimulus blur presented in this condition is above the threshold for automatic error correction (i.e. out of range). If subjects are able to reduce even a small portion of the added plus dioptric blur this may hypothetically reduce the trapezius muscle load (Richter et al., 2005). It should also be borne in mind that blur is an indication of defocus but is an ambiguous signal as to the direction of defocus and that some subjects therefore may respond to the +D blur by increasing the accommodation/vergence response. See Fig. 2.

The instruction used here was adopted from Richter et al. (2000): *Focus your eyes on the target so that it is maximally sharp and clear throughout the trial – maintain fixation*. Sustained attention throughout all experimental conditions was promoted by requiring the participants to monitor and report 30 intermittent

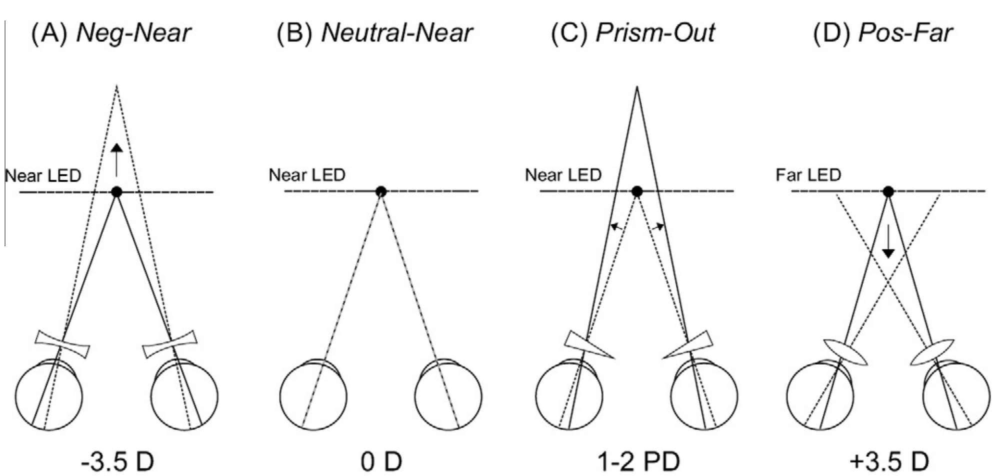

Fig. 2. Schematic illustration of the accommodative and convergence stimulus dioptric consequences of the different lenses used in the experiment (stippled line = accommodation; full line = convergence). (A) *Neg-Near*, (B) *Neutral-Near*, (C) *Prism-Out*, and (D) *Pos-Far*.

and brief (500–1500 ms) decreases of the target's luminous intensity. The intervals between two intensity decreases were of random length but always more than 4 s and less than 14 s. Participants reported the presence of decreases in luminosity by gently pressing a low-force push-button that was held in their right hand. Equal emphasis was put on speed and accuracy. A correct response ('hit') was defined as a push of the button occurring in a time interval of 100–2000 ms after the start of a light intensity decrease; responses recorded outside this period were considered as false reports.

2.6. Data processing

The data from the optometer was imported to MATLAB 7.1 (MathWorks, Inc.) where recordings outside of the optometer's linear range and outliers were excluded. Data in which the gaze position exceeded 25° from the pupillary axis were also excluded. Next the data were filtered with a rectangular moving average filter of 20 samples and resampled at 1.25 Hz. The refraction data from the subject's right and left eyes, the so called response dioptres, was thereafter compared to stimulus dioptres. Stimulus dioptres constitute the sum of the distance between the fixation target and the eyes and the inverse of the power of the ±D lens placed immediately in front of the eyes. Response dioptres are equivalent to the amount of accommodation of the eye-lens and/or vergence of the visual axis which occurred in response to a given amount of stimulus dioptres. When a lens is placed in front of the eyes of a participant, the optometer records the refraction power of both the eye-lens and the external trial lens. To obtain the value of the light refraction performed by the participant's eye-lens (response dioptres), the power of the optical lens was subtracted from the optometric output values. If a participant is able to focus at the expected distance and to compensate for the blur induced by the optical lens, the response dioptres will be equal to the stimulus dioptres. The difference between response dioptres and stimulus dioptres hereafter refers to residual blur. Residual blur may be attributed to an inability to compensate for the blur induced by the optical lenses and/or an inability to posture the accommodation/vergence response at the prescribed distance. If residual blur is close or equal to zero this means that the subjects have complied with the task to focus the eye-lens on the target as well as the instruction to nullify the added lens blur and converge the visual axis to the target of regard. In the present analysis both the response dioptres and residual blur provide measures of the degree to which a subject's accommodative/vergence system was loaded.

To render the recorded refraction data into a format that allows direct comparison with the stimulus dioptres two steps were taken. First the reference was shifted from the default distance of 1 m to optical infinity (i.e. to a reference which normally equals a minimum of load on the oculomotor system). This was accomplished by taking one minus the autorefractor output:

$$\text{refraction}^{\infty} = 1 - (\text{autorefractor output}) \tag{2}$$

The effect of the externally added lens' powers on the estimate of the accommodative/vergence response (referenced to infinity) was thereafter removed by the following calculation:

$$\text{response dioptres} = \text{refraction}^{\infty} - (\text{trial lens}) \tag{3}$$

In this way the 'myopic' or 'hyperopic' measurement error in the output from the optometer (introduced by the optical trial lenses) was corrected for. For example if a subject is focused at a target placed at 5 D (20 cm) while a -3.5 D lens is added in front of the eyes, and he or she continues to posture the accommodation/vergence response at this target distance (despite the blur), the response dioptres would in reality be equal to 5 D but the refractive measurements obtained from the subjects eyes would read 1.5 D. 'Lens-free' accommodative/vergence response, in this example, is obtained in the following way: $1.5 - (-3.5) = 5$.

2.7. Statistical tests

Statistical analyses were performed in SPSS 15.0 for Windows (SPSS Inc., Chicago, IL, USA). Individual averages of accommodative-and-convergence response dioptres to stimulus dioptres in the *Neg-Near, Neutral-Near* and *Prism-Out* conditions were explored in linear regression analyses. Separate repeated-measure ANOVAs were run on the aggregated 'accommodation-and-convergence error' for both eyes with 'conditions' (*Neg-Near*, *Neutral-Near*, *Prism-Out*, *Pos-Far*) as within factor, and 'group' (asthenopic versus symptom-free participants) and 'order' (there were four different orders counterbalanced across participants) as between factors. The average percentage of hits for light dimming and reaction times were related to the response dioptres via correlation analyses. A repeated-measure ANOVA examined both the number of hits for light dimming and the reaction times with 'conditions' as within factor, and 'group' as between factors. The nonparametric Friedman rank tests in pairwise comparisons (baseline versus fixation tested in separate conditions), and post hoc tests were used to test for significant rank difference between EMG levels in baseline and fixation in the four experimental conditions. In the concluding analysis a bitwise linear regression analysis was performed between the amount of residual blur and EMG. The cut-off values used in the bitwise linear regression analysis were fixed and equal to the specific amount of defocus blur in D induced via the optical trial lenses in the four experimental conditions. The cut-off value represented a physiological reference which denoted the point along the oculomotor response continuum where the accommodation/vergence response was fully postured on the target and when further action of the ciliary and/or extraocular muscles began to compensate the defocus blur introduced by the optical trial lens. Hence the bitwise linear regression estimated two parameters: a constant for the EMG level on the negative (left) side of the cut-off value and a coefficient for the slope of a line, starting at the constant level at the cut-off value and increasing/decreasing on the right (positive) side of the cut-off value.

3. Results

The characteristics of the accommodative/convergence recordings generally appeared task-appropriate (Fig. 3). No systematic trend in the individual time-series data could be detected. Instead, individual trials showed a mixture of stable responses and slight increases or small decreases in accommodation/convergence performance. In the results reported below the average from the individual 5-min recording of accommodation/vergence was used as an index of ciliary muscle contraction/relaxation. This indirect measure of oculomotor load was analyzed together with trapezius muscle EMG.

3.1. Left and right eye refraction values

A repeated-measure ANOVA run on two within factors – 'eyes' (left eye versus right eye) and 'conditions' (*Neg-Near*, *Neutral-Near*, *Prism-Out*, *Pos-Far*) – on the average 'accommodation error' showed that it was appropriate to average the data from the left and right eye in order to simplify the data presentation and increase the number of estimates in the data set (i.e. the average was used when both eyes were detected by the optometer; when only one eye was detected, the value for that eye was used). The refractive measurements for both eyes were not significantly

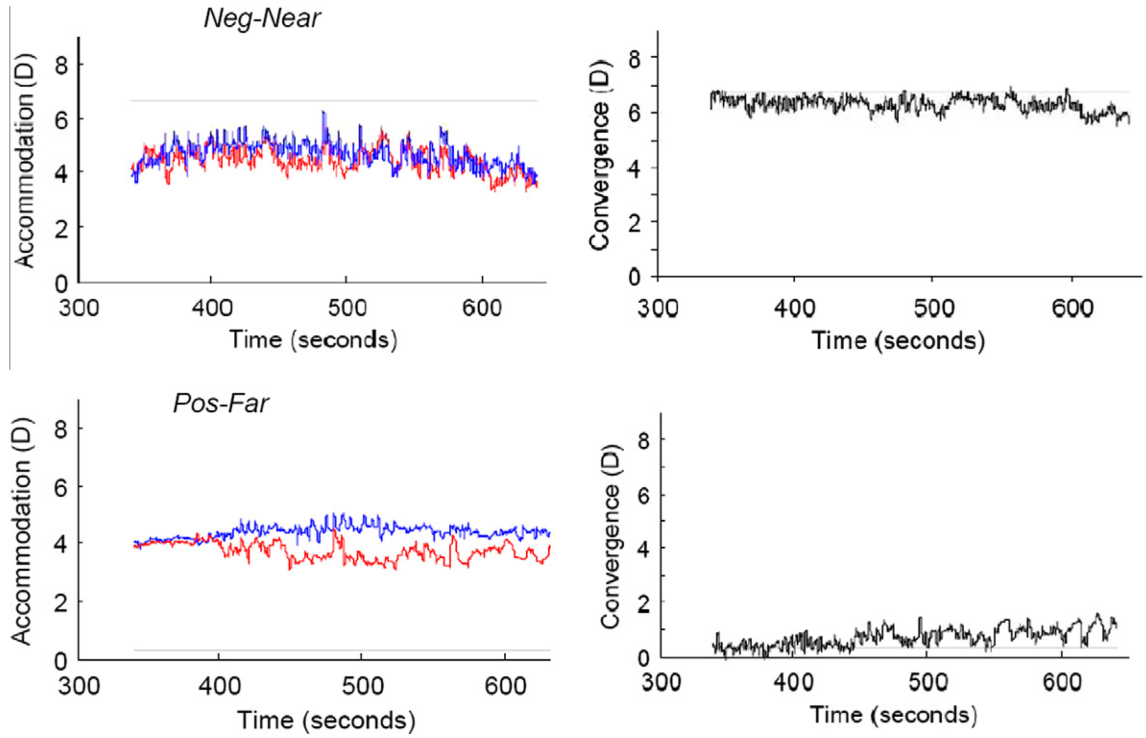

Fig. 3. Examples of 5-min recordings of accommodation and convergence data. Upper panels *Neg-Near*. The time-plot shows task-appropriate convergence responses. The data are aligned closely to the target (stimulus dioptres are denoted by the gray reference line). The eye-lens data show a tightly coupled left-eye and right-eye movement of activity. Both are under-focused relative to the stimulus. Lower panels *Pos-Far*. The convergence data from this subject is task-appropriately postured onto the target at far whereas the eye-lens data exhibit a considerable amount of residual blur (denoted by the distance between the eye-lens data and the stimulus line). Note that fusion between the left and right eye appears broken in this subject, indicative of the fact that the system is rendered open-loop due to the large amount of defocus blur.

different from one another ($F(1, 12) = 1.225$, $p = 0.290$), nor in interaction with the four experimental conditions ($F(3, 36) = 1.129$, $p = 0.350$).

3.2. Stimulus versus response dioptres

Both the accommodative and convergence averaged responses were significantly coupled to the individually determined stimulus distance which varied with age in *Neg-Near*, *Neutral-Near* and *Prism-Out* ($p < 0.001$) (Fig 4). There was no statistically significant difference between the accommodative errors ($F(1, 13) = 2.096$, $p = 0.171$) and convergence errors ($F(1, 17) = 0.901$, $p = 0.356$) between healthy subjects and subjects with eye and neck disorders, nor any interaction with conditions ($p > 0.05$). The 'accommodative errors' depended strongly on condition $F(3, 39) = 307.640$, $p = 0.001$, $\eta 2 = 0.959$. Post hoc pairwise comparisons showed that the average value of 'accommodative errors' was maximally negative in *Neg-Near* relative to the three other conditions and most positive in *Pos-Far* relative to the three other conditions ($p = <0.001$). The main effect of condition on convergence errors was also statistically significant, $F(3, 51) = 3.570$, $p = 0.020$, $\eta^2 = 0.174$. However the convergence errors exhibited overall smaller magnitudes (Fig. 4). The ANOVA also showed a significant effect of the covariate 'order' $F(3, 13) = 4.121$, $p = 0.029$, $\eta^2 = 0.487$ and an interaction of 'order' with 'condition' $F(9, 39) = 3.226$, $p = 0.005$, $\eta^2 = 0.427$ in the case of accommodation errors. Residual blur during *Neg-Near* in the 3rd or 4th order showed conspicuously large magnitudes (Fig. 5).

The *Neutral-Near* eye-lens residual blur averaged −0.57 D (range −3.07 to 0.98, std 0.91) while the average convergence response exhibited an error of 0.09 D (range −0.51 to 0.96, std 0.34). On the average the *Prism-Out* eye-lens refraction data exhibited an error value of −0.53 D (range −2.61 to 1.02, std 1.03) while the average convergence response exhibited an error value of 0.25 D (range −0.71 to 1.33, std 0.50). On the average the *Neg-Near* eye-lens refraction values were −3.04 D under-focused ('hypermetropic') relative to the individual stimulus dioptric values (range −6.47 to 0.13, std 1.64) while the average convergence response error exhibited a value of 0.01 D (range −0.85 to 2.04, std 0.59). On the average the *Pos-Far* eye-lens refraction data was over-focused ('myopic') by 4.0 D (range 2.17–6.09, std 0.94) while the convergence response exhibited 0.66 D myopia (range −1.40 to 2.16, std 0.88).

The individual measures of accommodation and convergence response dioptres were coupled with one another during *Neg-Near* (R^2: 0.804, $p < 0.001$), *Neutral-Near* (R^2: 0.864, $p < 0.001$) and *Prism-Out* (R^2: 0.811, $p < 0.001$). During *Pos-Far* accommodation and convergence response dioptres appeared uncoupled with one another (R^2: −0.118, $p = 0.573$).

3.3. Reports of light dimmings during the fixation periods

The average percentage of hits for light dimmings were 73 for *Neg-Near* (std 7), 56 for *Neutral-Near* (std 8), 59 for *Prism-Out* (std 8) and 80 for *Post-Far* (std 9). The averaged reaction times (ms) were 690 for *Neg-Near* (std 189), 762 for *Neutral-Near* (std 223), 767 for *Prism-Out* (std 250) and 603 for *Post-Far* (std 208). Correlation analyses showed that neither the number of correct answers nor the reaction times were associated with the amount of residual blur in any experimental condition. Hence the presence of more or less induced blur did not account for the variability in reporting light intensity decreases. Repeated-measure ANOVA showed however that both the number of hits and the reaction times were affected by the conditions, but not by the group of participants. For the effect of 'condition' on the number of correct responses, $F(3, 78)=7.360$, $p < 0.001$, $\eta^2 = 0.221$, and on the reaction

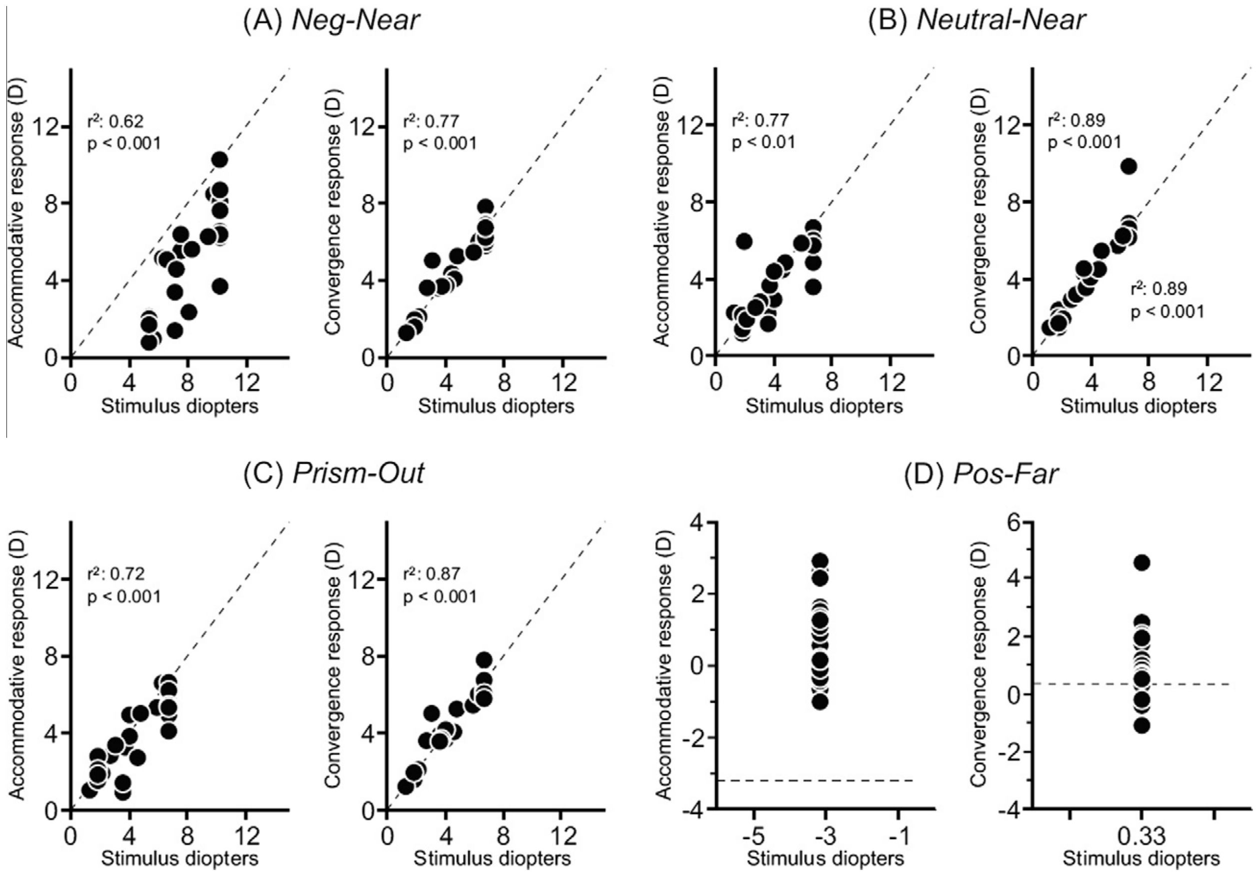

Fig. 4. Averaged accommodation and vergence responses versus stimulus blur across the different experimental conditions. The abscissa is stimulus dioptres and the *y*-axis is response dioptres. The stippled reference line represents unity between these variables. (A) *Neg-Near*, (B) *Neutral-Near*, (C) *Prism-Out*, and (D) *Pos-Far*.

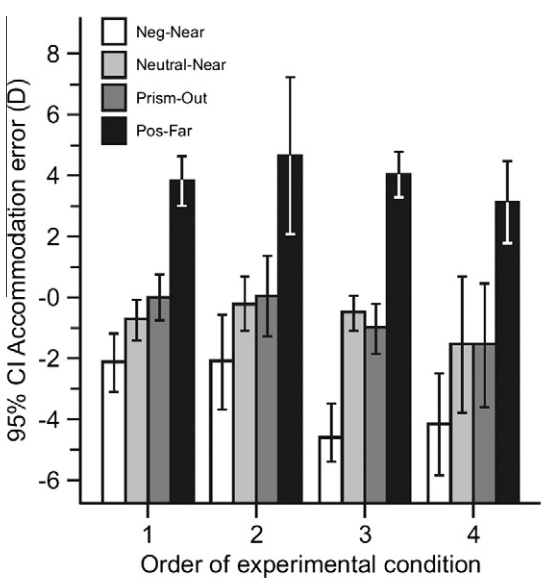

Fig. 5. Order effects on accommodative errors (residual blur) in the different experimental conditions. Note that the *Neg-Near* condition exhibits a conspicuous increase in magnitude of defocus blur when occurring third or fourth in the experimental order.

times $F(3, 69) = 5.592$, $p = 0.002$, $\eta^2 = 0.196$. Pairwise comparisons (with Bonferroni corrections) indicate that the number of correct answers was larger ($p < 0.05$) in *Neg-Near* and *Pos-Far* than in *Neutral-Near* and *Prism-Out*; the reaction times were significantly smaller only in *Pos-Far* compared with *Neutral-Near* ($p = 0.022$).

3.4. Trapezius muscle EMG across task conditions

The nonparametric Friedman rank tests in pairwise comparisons (baseline versus fixation tested in separate conditions) and post hoc tests showed a significant rank difference between baseline and fixation in the condition *Neg-Near* ($X^2(1) = 9.143$, $p = 0.002$ for the right shoulder, and $X^2(1) = 5.143$, $p = 0.023$ for the left shoulder); in the condition *Pos-Far* ($X^2(1) = 7.000$, $p = 0.008$ for both shoulders); in the condition *Neutral-Near* ($X^2(1) = 11.571$, $p = 0.001$ for the right shoulder, and $X^2(1) = 9.143$, $p = 0.002$ for the left shoulder). In the condition *Prism-Out* the rank difference was significant only for the right shoulder ($X^2(1) = 5.143$, $p = 0.023$, and $X^2(1) = 2.286$, $p = 0.131$ for the left shoulder). The rank was always higher during fixation than at baseline.

Friedman rank tests showed no significant difference between the four baselines, preceding each of the four experimental conditions ($X^2(3) = 0.432$, $p = 0.934$ for the right shoulder and $X^2(3) = 1.886$, $p = 0.596$ for the left shoulder). Nor during fixation did Friedman rank tests show any significant difference across conditions ($X^2(3) = 5.339$, $p = 0.149$ for the right shoulder and $X^2(3) = 5.792$, $p = 0.122$ for the left shoulder).

3.5. Effects of oculomotor load on trapezius muscle EMG

The described bitwise linear model was fitted to the 50th percentiles of the normalized EMG RMS values in each of the four conditions. Since no signs of differences between the left and right trapezius were seen, the mean of the two sides of EMG was used in the model fit. A significantly positive slope coefficient with increasing signed residual blur values, i.e. increasing oculomotor load, were seen in the *Neg-Near* and *Pos-Far* conditions ($p < 0.01$; in each of the four cases), see Fig. 6. This figure also shows that the model fit parameter was the highest in these cases, with R^2 between 0.316 and 0.38 and R^2 close to zero (<0.08) in conditions *Neutral-Near* and *Prism-Out.* The convergence response was completely unrelated to the trapezius muscle EMG in all experimental conditions.

4. Discussion

The objective of the present investigation was to see if sustained periods of static accommodation/vergence load has a significant effect on muscle activity in the neck, with more oculomotor load leading to more trapezius muscle EMG activity. The results show that increasing the tone of the ciliary muscle, by placing an optical minus lens in front of the eye and at the same time seeing to it that the lack of focus incurred is compensated for by increasing eye-lens accommodation, was observed to be significantly coupled to a bilateral increase in trapezius muscle activity in a time integrated dose–response manner. These results suggest that sustained eye-lens accommodation has the ability to regulate gaze by triggering a postural stabilization response.

4.1. Oculomotor processing during target fixation

Retinal image quality is largely determined by the accuracy and stability of the accommodative response (Franzén, Richter, & Stark, 2000). The quality of the static accommodative response is determined in turn by the balance of defocus-driven and convergence-driven accommodation (Ciuffreda, 1998). The accommodative and convergence errors during *Neutral-Near* and *Prism-Out* were both relatively minimal and strikingly similar to one another. Thus all subjects appear to have accommodated their eye-lens by contracting the ciliary muscle and converged their eyes, using the extraocular muscles appropriately. The accommodative responses also appeared cross-linked with the convergence. Considering the relatively impoverished viewing conditions, the group average of the steady-state accommodation/vergence response reported here is acceptable. This result gives credence to the validity of the results discussed below and to the procedures employed here to collect and analyze the data (Richter, Crenshaw, et al., 2007).

During *Neg-Near* the subjects generally converged appropriately but failed to completely nullify the −3.5 D lens blur. Negative residual blur values <−3.5 D in 42% of the subjects indicate that several subjects not only exhibited a lack of ability to nullify the induced lens blur but also experienced evident problems in accurately posturing their accommodative response to the near target. In this respect it is interesting to note that the participants who were assigned an order of experimental conditions such that *Neg-Near* appeared last or second to last were overall less able to compensate for the induced blur, probably due to accumulated fatigue (Fig. 5). Notably the convergence error showed no such effect of order. Extended periods of large amplitudes of ocular accommodation, when the ciliary muscle is contracted close to its maximum, i.e. during high levels of oculomotor load (Fisher, 1977), violate the basic ecological functions for which the visual system is adopted. This probably resulted in a loss of force-generating capacity and an inability to sustain fixation. The remaining 58% of the refraction data verified that subjects did reduce the minus dioptric blur to various levels of success (i.e. residual blur > −3.5 D). These results are in line with several reports which describe in detail rapid learning and execution of reflexive or volitional increases in dioptric strength of the crystalline eye-lens (Campbell & Westheimer, 1960; Ciuffreda & Kruger, 1988; McLin & Schor, 1988; Provine & Enoch, 1975). Campbell and Westheimer (1960) for example measured voluntary positive accommodation up to 3.0 D using a continuous recording optometer. Provine and Enoch (1975), moreover, successfully trained subjects to generate 9.0 D voluntary positive accommodation to nullify the effects of a −9.0 D contact lens.

During *Pos-Far* the subjects' accommodation/vergence responses, as expected, were not generally postured on target (Westheimer, 1957). The residual blur data instead indicates that the great majority of the subject's accommodative/vergence response was postured at a much closer range. In the absence of adequate stimulus contrast, accommodation gravitates towards, or adopts, an intermediate focus value referred to as the neural 'resting position' (the magnitude of which is known to be dependent on the concurrent balance between the parasympathetic and sympathetic innervation to the ciliary muscle and to display considerable between-subject variability. See Gilmartin, 1986). The average accommodative response dioptres during *Pos-Far* was 0.82 D (std

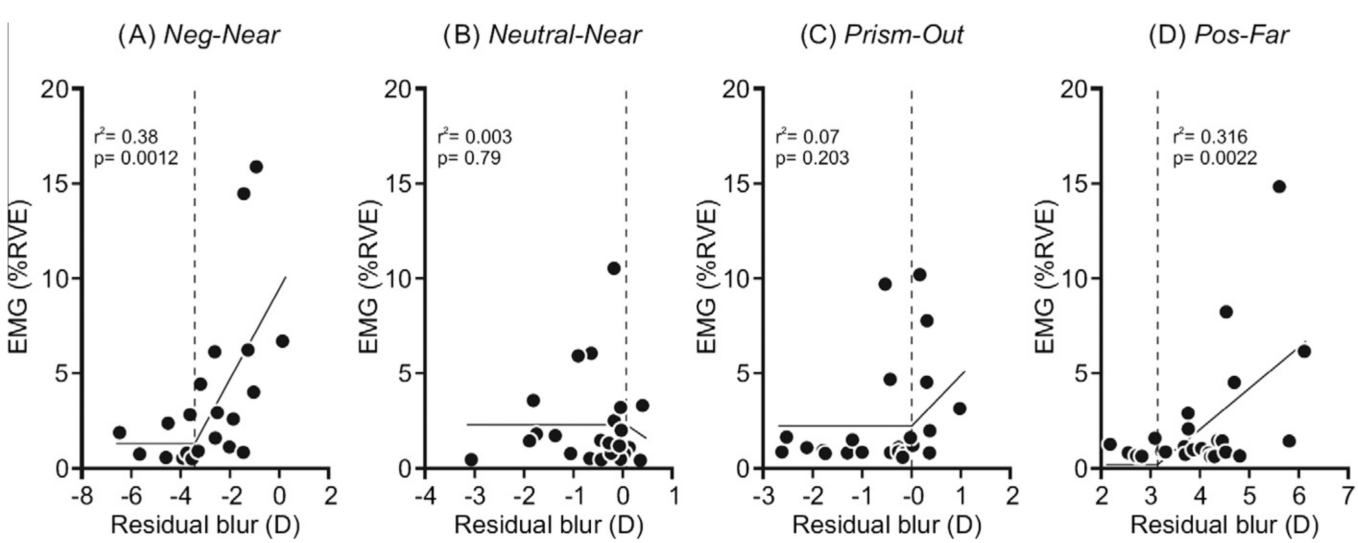

Fig. 6. Normalised trapezius median EMG levels during sustained accommodation/vergence to the target seen through: (A) −3.5 D (*Neg-Near*), (B) 0 D (*Neutral-Near*), (C) 1–2 Prism D (*Prism-Out*) and (D) +3.5 D (*Pos-Far*). The cut-off values used in the bitwise linear regression analysis (stippled reference line) were fixed and equal to the specific amount of defocus blur induced via the optical trial lenses in the four different experimental conditions. A value of 0 D on the *x*-axis indicates a correctly postured eye-lens response, which has also nullified the induced blur.

0.94), which is reasonable close to earlier reported estimates of resting focus values (the so called 'dark-focus') (Leibowitz & Owens, 1978). The individual averaged accommodative and vergence responses were also disassociated from one another. Taken together these circumstances suggest that the accommodative system was rendered open-loop by the plus lenses. Generally two types of accommodative responses may be discernable in *Pos-Far*. First, residual blur values >+3.17 D indicate that subjects either responded 'passively' by letting the accommodative response gravitate towards its neurologically determined resting point or 'actively' by eliciting positive accommodation. Second, the occurrence of residual blur values <+3.17 D also indicates that a few subjects responded with so called negative accommodation (Hofstetter et al., 2000). Under extraordinary conditions, such as in the present open-loop condition, a small portion of the accommodation/vergence response may be inhibited by voluntary control of accommodation/vergence (e.g., Angi et al., 1996; LeGrand, 1952; Raz, Marinoff, Landzberg, & Guyton, 2004b; Raz, Marinoff, Zephrani, Schweizer, & Posner, 2004a; Richter & Franzén, 1994; Richter et al., 2005).

Episodes of pupils of insufficient size were observed across all experimental conditions, particularly in *Neg-Near* and when the contractive force of the ciliary muscle approached its maximum (cf. Wolffsohn et al., 2002). The synkinetically stimulated decreases in pupil size precluded a complete recording of the accommodative response of the crystalline eye-lens. This measurement inaccuracy, due to occasional sections of missing data, renders the previous estimates of residual blur overly conservative (i.e. the degree of task compliance is underestimated). This circumstance does not impact however on the validity of the measure of the relative coupling between the eye/neck–scapular area interactions.

4.2. Effect of visual attention during the fixation periods

The larger number of correct answers and faster responses in *Pos-Far* may be attributed to the fact that the light decreases were easier to detect in the distant target (due among other things to uncorrected plus lens-induced optical magnification). The larger number of correct answers in *Neg-Near* as compared to *Neutral-Near* ($p = 0.003$) and *Prism-Out* ($p = 0.011$) is somewhat more intriguing, as the target is the same and located at the identical distance in the three 'near' conditions. Improved detection of light intensity decreases in both *Neg-Near* and *Pos-Far* might be a consequence of the brain imposing an enhanced analytic structure on the ascending sensory information during ongoing eye-lens accommodation such that relatively more priority is given to sensory information in the central fovea (cf. Richter, Wennberg, & Raudsepp, 2007; Richter et al., 2000; Richter et al., 2005). The observed lack of correlation between residual blur and response

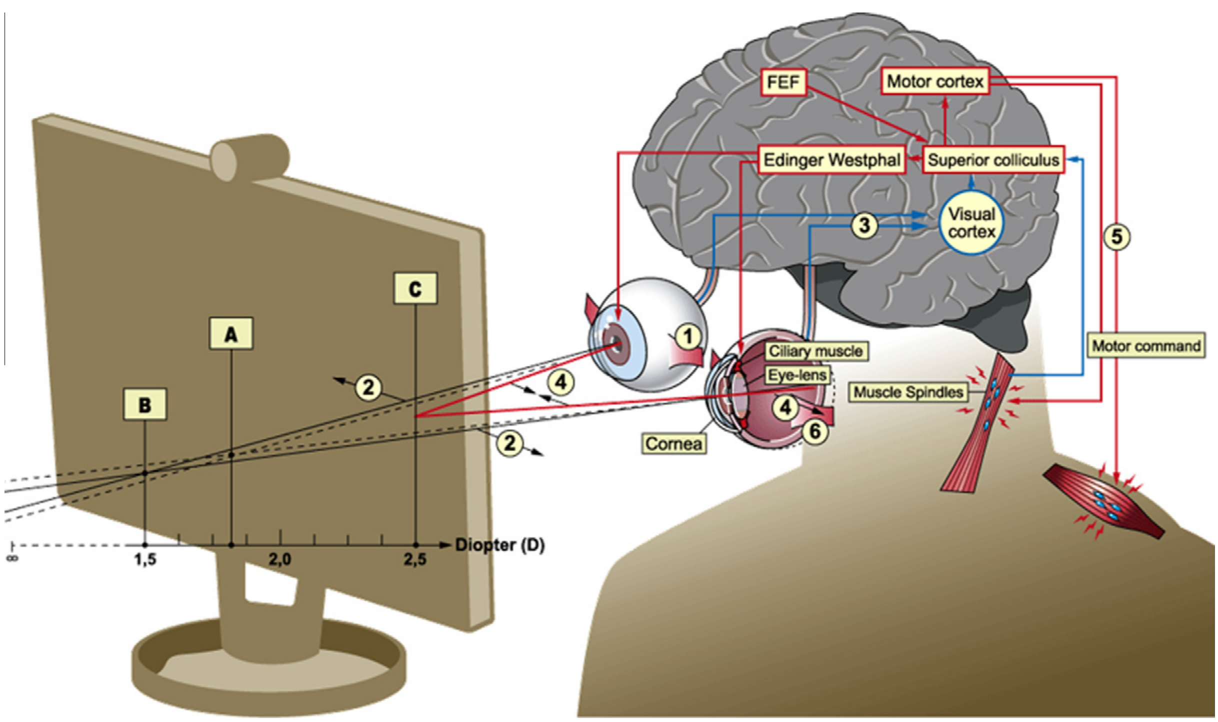

Fig. 7. Summary of present and previous experimental results and a theoretical account of visuomotor loops thought to underly gaze stabilization. The figure shows tentatively central nervous system reflexes which may be activated during normal viewing conditions such as professional information technology work and, as investigated in the current study, when an accommodative/vergence foci (A) fatigues following strenuous near work and as a consequence temporarily dissociates into either a fatigued convergence foci (*Prism-out*) or (B) a fatigued accommodative foci (*Neg-Near*, not shown), either of which may be harnessed via compensatory eye-lens accommodation (C). More specifically, when the oculomotor system (1) fatigues following intense near work, the optical axis may momentarily diverge relative to the target of regard (2). The eye-lens may similarly no longer be optimally focused and blur and/or double vision in the retinal image results (3). Under such adverse circumstances a compensatory response may be elicited by the central nervous system, with the goal of realigning the oculomotor response onto the target (4). The neural correlates may include the frontal eye field (Bizzi, Kalil, & Morasso, 1972; Corneil et al., 2002; Corneil, Munoz & Oliver, 2007; Elsley, Nagy, Cushing, & Corneil, 2007; Guitton & Mandl, 1978; Sumner, Nachev, Castor-Perry, Isenman, & Kennard, 2006; Tu & Keating, 2000), which make large projections to the intermediate and deep layers of the superior colliculus. When triggered by strenuous near work, frontal eye field efferentation may cross over to motor tracts and thus drive and posture the visual-musculoskeletal effectors in a synergistic fashion that is more than what is optimal from a musculoskeletal health point of view (Lie & Watten, 1987; Richter et al., 2005; Richter, Bänziger, & Forsman, 2010). The end result achieved may be 'too much' gaze stabilization. Afferentation from muscle spindles may signal when gaze stabilization has been achieved. Neck–scapular area muscle activation, caused by oculomotor responses to strenuous near work, when accumulated over time, may give rise to a broad spectrum of musculoskeletal problems and disorders (Franzén et al., 2000; Hägg, 1991, 2003; Johansson et al., 2003). An altered musculoskeletal pattern of gaze stabilization may occur in individuals with chronic work-related myalgia.

times or number of correct responses and residual blur verifies that the trapezius muscle activity reported in both of these conditions was not a main consequence of attention load (cf. Corneil, Munoz, Chapman, Admans, & Cushing, 2008; Kunita & Fujiwara, 1996).

4.3. Eye–neck/scapular area interactions

The *Neutral-Near* and *Prism-Out* conditions did not induce trapezius muscle EMG activation that was significantly associated with residual blur. In the *Prism-Out* condition the lack of significance may in part be related to the placement of the cut-off line used in the bitwise regression analysis. An alternative placement of the cut-off line on the point which explained maximum of the variance, namely -1.6 D instead of 0 D, did improve the model fit, i.e. the slope coefficient between residual blur in *Prism-Out* versus the 50th percentile EMG became marginally significant with an alternative placement of the physiological reference for accommodation/vergence effort (R^2: 0.28, $p = 0.054$). In both the *Neg-Near* and *Pos-Far* viewing conditions a time integrated dose–response relationship between eye-lens residual blur and trapezius muscle EMG activation revealed itself. For those subjects that did not comply with the task to compensate the blur due to fatigue (or some other idiosyncratic reason), the trapezius muscle activity remained within a state which is normally considered to constitute physiological rest (<2.5% relative voluntary contraction approximately equal to 0.5% maximum voluntary contraction. See: Nordander et al., 2000; Veiersted, Westgaard, & Andersen, 1993). As mentioned above, a subset of subjects in *Pos-Far* seemed to have contributed to the residual blur by inadvertently tensing their ciliary muscles rather than relaxing it, which would reduce the residual blur. In these cases EMG activity was again augmented in a time integrated dose–response dependent way. Hence the force of contraction of the ciliary muscle (Fisher, 1977), in either case, seems to be a key mediating trigger for a centrally controlled eye/head–scapular area motor program, i.e. the neural circuits which cause physiological levels of muscular tension in the neck and shoulder to co-vary with efference to the ciliary muscle.

The trapezius muscle activation, which was above resting level, may be attributed to the reflex optic paths being at the origin, not only of the ocular responses, but also of the extraocular and neck and scapular muscles (Corneil, Olivier, & Munoz, 2002; Kapoula & Lê, 2006; Richter, 2008; Richter, Costello, Sponheim, Lee, & Pardo, 2004). Voluntary or reflexive accommodative/vergence effort in response to oculomotor fatigue (which elicits extra efferentation to the eye-muscles to counteract this tiredness) may, as an unwarranted consequence, cause a dysfunctional tonus increase and/or reduced load variation in the neck, scapular area muscles and upper back (Richter et al., 2005; Valentino & Fabozzo, 1993). In all likelihood adjustments of eye-lens accommodation to a blurred target reflexively activate a hard-wired cortical stabilization processes which links the eye-neck/scapular area effectors with one another to ensure that the target is held in the retinal area of highest visual acuity. The bilateral patterns of evoked trapezius muscle activation in *Neg-Near* and *Pos-Far* are consistent with this view. Notably, visual targets 1° or further away from the fovea constitute inadequate sensory stimuli to elicit or drive the accommodative response (Richter et al., 2000, 2005). This highly specialized part of the fovea encompasses less than 0.03% of the surrounding environment. See Fig. 7.

Previous results of studies of chronic pain suggest that the neuromuscular pattern underlying gaze stabilization may be altered in individuals afflicted by chronic work-related myalgia (Passatore & Roatta, 2006; Richter, Röijezon, Björklund, & Djupsjöbacka, 2010). Muscle spindles have for example been proposed to play a major role in increasing muscle tone and in the pathophysiology of muscle pain syndromes (Johansson, Windhorst, Djupsjöbacka, & Passatore, 2003). The superior colliculus also receives an abundance of afferentation from neck/scapular area muscles which, if aberrant, could play a role in sculpturing an overly rigid posture characterized by "to much" musculoskeletal activation (Djupsjöbacka, 2003; Meulenbroek, Van Galen, Hulstijn, Hulstijn, & Bloemsaat, 2005). However, no group effect was discernable on the evoked trapezius muscle EMG in the present study and this apparent discrepancy therefore remains unsettled. Future studies should include better characterized study participants. A related limitation in the present study is the constrained posture. Because the eyes had to be aligned to the axis of the optometer, movements from the neck/scapula area were not allowed. Gaze stabilization should ideally be studied under conditions where the head is allowed to move freely (Martinez-Trujillo, Klier, Wang, & Crawford, 2003). Additional important issues for future research include elucidating how the gaze stabilization response is distributed to different muscles. The trapezius muscle studied here is only one muscle out of approximately two dozen which operate to stabilize the head/neck–scapulae and/or move it to adequate postures (Corneil, Olivier, Richmond, Loeb, & Munoz, 2001). Finally, it should be emphasized that surface EMG offers excellent opportunities to study the 'brain in action', i.e. how the CNS sends efferent commands to peripheral effectors, and also provides important clues to how visual system processing impacts on these processes. However surface EMG may nevertheless not be sensitive enough to determine whether the gaze stabilization response characterized here also arises during normal or less strenuous accommodative/vergence viewing conditions, as recruitment of deeper muscles in particular may go unnoticed.

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