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Review

Accommodation/vergence eye movements and neck/scapular muscular activation: Gaze control with relevance for work-related musculoskeletal disorders

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ABSTRACT

The accommodative system of the eye adjusts the curvature of the crystalline eye lens, thereby changing the refractive power enabling the eye to focus a clear retinal image of objects at near or far distances. With the arrival of more accessible measuring techniques and the proliferation of a multi-disciplinary scientific approach, progress has recently accelerated in this area of visual neuroscience. It is becoming clear that the process of adjusting the focal power of the eye, to enable clear vision at near or far distance, gives rise to complex elaborations of nerve signals in central and peripheral sensorimotor circuits. When the force of contraction of the ciliary muscle reaches a critical threshold, a universal eye-head-neck-scapular motor programme responsible for posturing gaze is launched. Under these conditions, the activity of the trapezius muscle is raised above a level that is considered as the physiological rest. Simultaneous with the increases in musculoskeletal activation levels, regional cerebral blood flow (rCBF) in visual cortex is raised above a level that occurs naturally during normal fully focused viewing conditions, whereas frontal systems specialized for visual search become down-regulated. The interpretation of the rCBF changes is that the brain imposes 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. The implications of the newly discovered mechanism for gaze control are discussed within the realm of basic and applied ergonomic research with a specific emphasis on musculoskeletal disorders and visual ergonomics.

KEYWORDS: accommodation, asthenopia, convergence, musculoskeletal, pain, workplace

INTRODUCTION

Disorders from the visual and musculoskeletal systems are major public health problems affecting substantial proportions of the general population in their work, daily living and social life. The National Institute for Occupational Safety and Health (NIOSH) in the USA reports that over 80% of those who work with computers suffer from these complaints. The understanding of the causes to these lingering work-environment problems remains a major economic and social challenge. Computer work has come to dominate modern working life. About 75% of the work-force in many countries use computers in their work. According to a recent estimate, the Internet is used by 29% of the world's population and this usage is rising.

In addition, new technology is steadily on the increase (smartphones, iPads, etc.). Even though

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the literature supports the notion that eye strain and neck/scapular area symptoms are common and coexisting complaints among employees in modern offices, the two symptom categories are often analyzed in isolation within disparate disciplines of applied or clinical science. Accordingly, the evidence for linkages between eye strain and neck/shoulder complaints so far is limited.

The near response

In order to perceive small details in the surround (e.g. an alphanumerical character displayed on an electronic screen), the light has to be appropriately refracted. The process of adjusting the curvature of the crystalline eye lens, which brings images into sharp focus in the plane of the retina, is called accommodation. The accommodative response consists of a tightly coupled triad of eye movements: dioptric (D) adjustment of the crystalline eye lens; convergence⁄divergence of both eyes toward the locus of fixation; and pupillary constriction⁄dilatation. The accommodative system of the eye adjusts the curvature of the lens, thereby changing its refractive power, allowing the formation of a clear retinal image of an object located at a different distance than the present. This reaction is controlled by the ciliary muscle which changes the curvature of the lens. The most important stimulus for ocular accommodation is a blurred image. Hence, if an object of regard falls outside a viewer’s present depth-of-focus, it appears fuzzy and its subjective contrast is reduced, due to a decrease in contrast modulation of the retinal image. The cornea, the aqueous humour and the vitreous body all have a fixed refractive power, while the lens can change its accommodative strength by changing its curvature. Thereby it adjusts its focus relative to the object of inspection. At around 40 years of age, when one’s clinically-derived accommodative amplitude has decreased to about 5 D, individuals typically require optical correction for near work to see clearly to compensate for this physiological loss. In contrast to the muscles that control the movements of the eye, the smooth muscles that regulate the size of the pupil and the curvature of the lens are innervated by the autonomic nervous system. An increase of the curvature of the crystalline eye lens is mediated by parasympathetic branches of the autonomic nervous system. A supplementary inhibitory system is furnished by the sympathetic nervous system [1, 2]. The sympathetic inhibition is relatively small (< 2.0 D), slow with time courses between 20-40 s (compared with 1 or 2 s for the parasympathetic system)-and augmented by a substantial concurrent background level of parasympathetic activity [2]. The ciliary muscle is unique among all parasympathetically dominated smooth muscles in the body because it has many characteristics of fast striated muscles [3]. It should be emphasized that the term ‘autonomous’ is somewhat misleading in this context since the eye-lens accommodative system is under considerable influence of higher central mechanisms. Increasing cognitive demand has been shown for example, to have impact on accommodative responsiveness, effects which have been attributed to changes in autonomic nervous system efferentation to the ciliary muscle [4, 5].

Eye-neck/scapular area linkages

Although the neurological models of the accommodative focusing processing have reached an advanced state (Fig. 1), many questions remain unanswered about the intricate machinery of the human brain. The exact process by which the diotric error becomes transformed into a motor command for accommodation of the crystalline eye lens is unknown. Cortical processes preceding and monitoring the ciliary motor command are similarly poorly understood [6]. Nor is the nature of mental attentiveness as a control factor in dioptric focusing yet fully understood. With the discovery of new sensorimotor control processes and improved insight into mechanisms which link the visual and musculoskeletal system with one another, a systematic review of the circumstances under which a change in accommodation/ vergence loads actually leads to alterations in physiological levels of musculoskeletal tonus therefore appears timely. The threefold aim of this review consequently is: i) to highlight newly discovered sensorimotor control processes which in all likelihood are launched to monitor and supervise crystalline eye-lens accommodation; ii) to summarize new evidence linking eye-neck/scapular area effectors with one another and

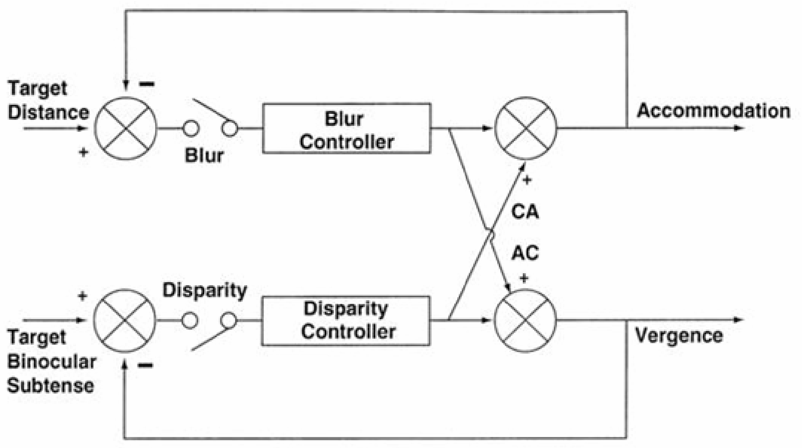

Fig. 1. Simplified dual interaction model of accommodation and vergence control (based on 9, 10, 11). Disparity-driven vergence signals influence accommodative output and, similarly, blur-driven accommodative signals influence vergence output. When an image of a visual target on the retina is blurred, approximately 500 ms elapse between the detection of the blurred target and the complete accommodative response to the target. During this time, neural circuits compute the location of the intended target, decide whether to focus on the intended target and initiate the accommodative response. Iterative computations tune the accommodative response based upon initial visual sensory cues, feedback and comparison with the internal representation of the target.

discuss possible mechanisms; and iii) to discuss the relevance of these results for gaze control and musculoskeletal disorders (for reviews dealing with more general aspects of crystalline eye-lens accommodation the reader is referred to e.g. 7, 8).

Cortical correlates to voluntary increases in accommodation⁄vergence

Regional cerebral blood flow increases in visual cortex

Using Positron Emission Tomography (PET), regional cerebral blood flow was explored in alert performing humans, under the condition of voluntary or reflexive control of the focusing process of the eye [12]. PET is based on radioactive decay of a labelled tracer occurring inside the brain. The PET camera shows blood flow to different areas of the brain; increased blood flow indicates increased brain activity and decreased blood flow indicates reduced activity [13]. Using this method Richter *et al.* [12] localized the cortical network responsible for the dioptric focusing process in humans. Neuronal activity in their study was estimated by measurement of changes in regional cerebral blood flow (rCBF) with PET and ^{15}O-water. A checkerboard pattern was viewed monocularly with the dominant right eye while an optical trial lens interrupted the line of gaze during alternating 1.5 s intervals. Three tasks required central fixation and viewing of the checkerboard pattern: 1) through a 0.0 diopter (D) lens (No-Blur); 2) through a -5.0 D lens while avoiding volitional accommodation and permitting blur (Blur); and 3) through a -5.0 D lens while maintaining maximal focus (voluntary positive accommodation, VPA). The latter required large amplitude and high frequency, voluntary accommodation (Fig. 2).

An eye-catching increase in rCBF occurred during VPA when compared to No-Blur in striate and extrastriate visual cortices. These activations were thought to reflect sensorimotor processing along the reflex arc of the accommodative/vergence system. Visual regions included the posterior portion of the calcarine cortex subserving the fovea, lingual and fusioform gyri and cuneus (Fig. 3).

The visual activation resulting from VPA, compared with the No-Blur viewing condition, was unexpected and cannot readily be explained. Even if the subjects were completely accurate in their accommodation (which is unrealistic), no visual activation during voluntary accommodation

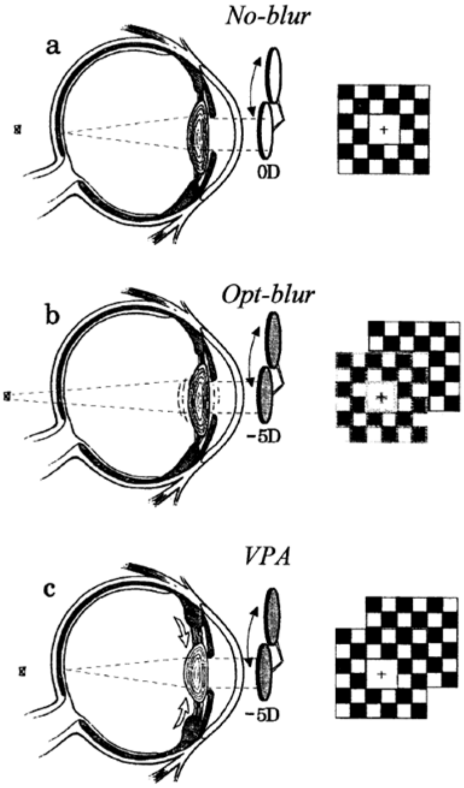

Fig. 2. Experimental design for neuroimaging of monocular voluntary accommodation/vergence eye movements. A) The No-blur condition (0 D) involved maintaining fixation while a 0 D lens was intermittently placed in the line of sight of the dominant eye. B) The Opt-blur condition required the subjects to avoid focusing on the checkerboard whenever a -5.0 D lens intermittently interrupted the line of sight. C) The condition, voluntary accommodation/vergence (VPA) required the subjects to maintain maximal focus on the checkerboard whenever the -5.0 D lens intermittently was placed in the line of sight and defocused the checkerboard [12].

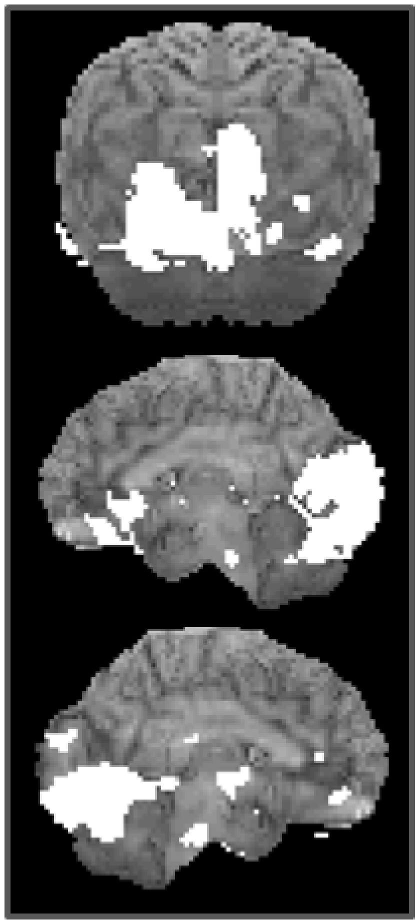

Fig. 3. Cerebral activation during voluntary positive accommodation. Surface rendering of activations along lateral and medial aspect of each hemisphere. Activation during voluntary accommodation (cf. Fig. 2C) as compared to “passive viewing” (cf. Fig. 2A). Threshold for these images set at Z=2.1 to optimally display the pattern of activity. Whiter colour denotes greater Z scores; white set to maximum. Panels show that voluntary accommodation is associated with posterior activations in occiput and cerebellum. The visual responses also show hemispheric asymmetry [12].

over that in No-Blur would be expected, based upon consideration of retinal contrast. The occipital activation may instead arise from local re-entrance within microcircuitry analogous to servo-mechanisms and be related to the formation of even and odd-error focusing signals [14, 15]. Cognitive top-down processing is another possibility. During visual accommodation the relevance of the target may be greatly increased, since its appearance will immediately govern the generation of motor command signals or conversely abolish such processes. Specifically, after execution of an accommodative response, re-regulation and/or fine-tuning of the motor output by afferent feedback may occur in order to appropriately posture the accommodative response onto a target. Effects of attention on primary visual activity (i.e. variations in sensory pathway gain, rate of encoding, or information extraction due to differential concentration of processing resources) may have occurred [16]. Sustained and directed attention is known to modulate the firing rate of individual neurons in somatosensory and visual cortex as early as in primary receiving areas [17]. Physiological and anatomical studies have supported the idea that early visual cortical areas may provide a general low-level pre-perceptual stage of processing of visual information that is then distributed into a hierarchy of visual pathways that are selectively engaged, depending upon processing requirements.

Perceptual capacity allocation to the fovea

The effect of sustained (7 min) eye-lens accommodation on visual processing in the fovea, when attempting to overcome optical blur, was recently re-investigated in a psychophysical task paradigm [18]. In this study, attention was promoted and controlled by requiring the participants to monitor and report 30 intermittent and brief (500-1500 ms) decreases of the target's luminous intensity. The high-contrast fixation target consisted of a bright X illuminated from behind with a polychromatic LED (Light Emitting Diode) that emitted a white colour. 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. There was a significantly larger averaged number of correct answers (73 [std 7] versus 56 [8]) and faster averaged response times (690 msec [std 189] versus 762 msec [std 223]) in the condition requiring eye-lens accommodation to overcome -3.5 D blur as compared to a non-blur condition (cf. Fig. 2 A-C). This finding was intriguing, as the target was the same and located at the identical distance.

The conclusion, derived from brain imaging and psychophysical studies combined, is that eye-lens accommodation does something more to visual processing than "merely" providing a focused retinal projection. During ongoing eye-lens accommodation to a blurred central target, the brain, more specifically, seems to impose an enhanced analytic structure on the ascending sensory information such that relatively more priority is given to sensory information in the central fovea. Sensory feedback consequences of an executed accommodative response, in all likelihood, are enhanced in order to optimally monitor and adjust an ongoing accommodative/ vergence response.

Disengagement of systems specialized for visual search

An inhibitory effect of eye-lens accommodation on systems specialized for visual search has previously been demonstrated. PET image averaging across subjects participating in voluntary or reflexive control of the focusing process of the eye demonstrated that decreases in rCBF occurred in the lateral intraparietal area, prefrontal and frontal and/or supplementary eye fields [12]. For example, the activity of the right premotor area BA 6 (frontal eye field, FEF) was significantly reduced during voluntary accommodation. This decrease was highly correlated with a concomitant activity decrease in the left parietal lobule (BA 39/40) ($r^2 = 0.65$, $p < 0.001$). The frontal rCBF decreases were interpreted as a disengagement of the systems specialized for visual search. Based on these findings and on close to identical results reproduced in two sequential studies (19, 20, see below), it was speculated that foveal fixation and a sharp retinal image have an inhibitory effect on peripheral perception, perhaps due to dual-task interference and central processing limitations. These results may also imply that foveal fixation and a sharp retinal image have a negative impact on the ability to process "task-irrelevant" events occurring in the "peripheral" stream of consciousness. Hence, signals arising from within the body, such as muscle pain, fatigue and anxiety, may go by more or less undetected during high levels of sustained accommodation/vergence. This circumstance, which has not yet been subject to scientific inquiry, could have implications for a broad range of work situations, particularly when high attention is demanded in the central visual field (i.e. during work with modern information technology devices).

Cortical correlates to voluntary inhibition of accommodation⁄vergence

rCBF decreases in frontal eye field and postcentral⁄precentral gyrus

During voluntary inhibition of accommodation⁄vergence compared with a resting state, Richter *et al.* [20] found rCBF increases in occipital cortex and decreases in superior parietal cortex (BA 5), frontal cortex (BA 6, 8 and BA 10) and within the postcentral/precentral gyrus (BA 1⁄2⁄3⁄4). Contralateral and ipsilateral deactivity foci, eclipsing both the primary motor cortex and the somatosensory cortex, occurred at somatotopic coordinates that implicated the ipsilateral neck and contralateral shoulder area [21]. A decrease in contractility of skeletal muscles and a consequential diffuse decrease in primary sensorimotor resting rCBF was a hitherto undocumented consequence of negative accommodation⁄vergence.

The superior colliculus, a small volume midbrain structure that plays an important role in triggering and organizing spatial-orienting movements, contains circuitry that together with covert spatial attention, a process that focuses attention on a region of space different from the point of gaze, could provide linkages between the accommodative/vergence and musculoskeletal system (cf. [22]). Local electrical stimulation of the superior colliculus in a variety of animals, including primates, produces orienting responses that may involve coordinated movements of the eyes, head and body [23] or lens accommodation and vergence eye movements or covert shifts of spatial attention [24, 25, 26]. The frontal rCBF decreases which occurred in the left hemisphere may belong to the circuitry related to inhibition of a centrally controlled eye-head-neck scapular area motor programme responsible for posturing gaze. Tu & Keating [27] demonstrated that repeated stimulation in monkeys, at either the left or the right FEF, evoked gaze shifts of roughly constant amplitude. These gaze shifts could be accomplished with varied amounts of head and eye movements, depending on their respective (head and eye) starting positions (see also [28, 29]).

Primary motor-somatosensory rCBF and models of work-related myalgia

The reduced primary motor-somatosensory rCBF during negative accommodation/vergence may be of relevance for models of neuromuscular mechanisms involved in chronic work-related myalgia [30]. For example, when oculomotor stress is created by sustained near fixation, muscle tension may be expected to increase not only in the accommodation and vergence muscles but also in the other muscles of the integrated head-neck scapular area muscle systems. Dysfunctional cross-modality processing between muscles with high spindle density, such as the extraocular, neck and scapular area [30] muscles, may occur under adverse circumstances [31, 32].

Ciliary muscle load and static neck/scapular area muscle activity

Lie and Watten [32] recorded the EMG activity of 10 subjects in six sites in the neck and scapular area, during a visual discrimination task when the accommodation and fusion requirements were systematically increased by first decreasing viewing distance (from 6 m baseline to 40 cm) and then placing minus lenses or base-out prisms in front of their eyes (cf. [31]). The EMG average amplitude from the four conditions was significantly higher than during baseline for five muscle sites (frontalis, deltoid, mid-trapezius, levator and upper trapezius). It was also increased for the masseter muscle, but not significantly. Their trend analysis showed progressively higher EMG amplitudes for all six muscles when the stimulation conditions changed from viewing at near distance to viewing at near distance with minus or prism lenses. Moreover, with the exception of deltoid, the same muscles showed reduced EMG in a clinical population of 31 subjects with chronic neck/scapular area problems under optimal optometric conditions as compared to habitual (inappropriate) correction, or relative to a convergence stress condition, during letter reading at 40 cm. In the Lie and Watten study, task compliance and individual level of oculomotor loads were largely accepted at face validity due to the technological limitations at the time of the testing. With the advent of infrared optometers that provide continuous in-vivo recordings of eye-lens accommodation, it recently became possible to probe deeper into the causes of the baseline shift in trapezius muscle activity via indirect measures of oculomotor load.

Trapezius muscle electromyographic activity

In experimental studies designed to follow up the results from the brain imaging and EMG studies, Richter *et al.* [18, 33] induced different levels of oculomotor load binocularly via optical lens blur. Electromyographic activity (EMG) during visually strenuous/fatiguing near viewing conditions was collected bilaterally from the descending part of the upper trapezius muscle. 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). The high-contrast fixation target consisted of a bright X illuminated from behind with a polychromatic LED that emitted a white colour. Defocus blur was introduced into the optical axis of the viewing eyes via -3.5 D lenses that were mounted in trial frames. The subjects were expected to compensate for the incurred blur by adjusting the dioptric strength of their crystalline eye-lens. Because the eyes had to be aligned to the axis of the optometer, movements from the neck/scapular area were not allowed. A bitwise linear regression model was fitted on group level with eye-lens refraction on the x-axis (i.e. an indirect measure of ciliary muscle load, see Fig. 4) 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 also had a slope, where the subjects had compensated.

The slope coefficient was significantly positive in the -3.5 D blur condition. During no blur (0 D) there were no signs of relationships (see Fig. 5). Nor was there any sign of relationship between the convergence response and trapezius muscle EMG in any of the experimental conditions. The results appeared 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.

Ocular accommodation and autonomic function

In parallel to the trapezius muscle EMG activations elicited by eye-lens accommodation Richter *et al.* [18, 33] recorded electrocardiography (ECG) to assess the heart rate (HR) and heart rate variability (HRV) as markers of autonomic reactivity. As individuals afflicted by chronic work-related myalgia and/or professional

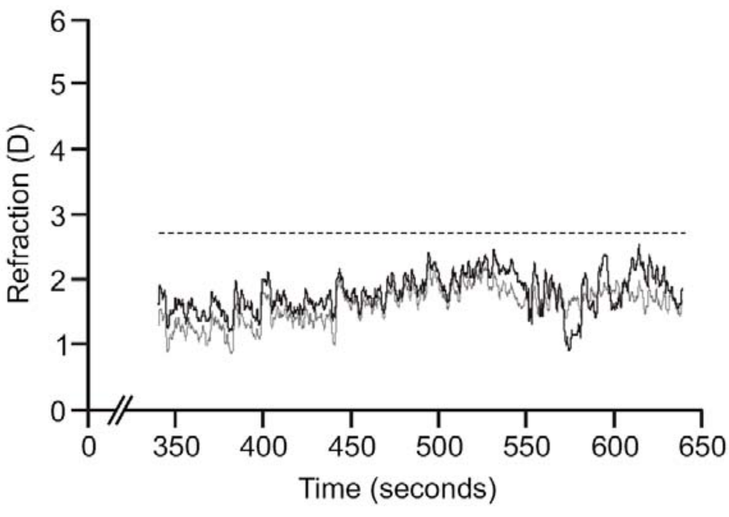

Fig. 4. Example of a five-minute recording of sustained accommodation/vergence to a target seen through -3.5 D. The eye-lens data show a tightly coupled left-eye and right-eye movement of activity (right denoted by black, left by grey lines). Both are under-focused relative to the stimulus dioptres. The residual blur (denoted by the distance between the eye-lens data and the stimulus line) was used as an indirect measure of contraction of the ciliary muscle, with less residual blur implying more contraction and vice versa [33].

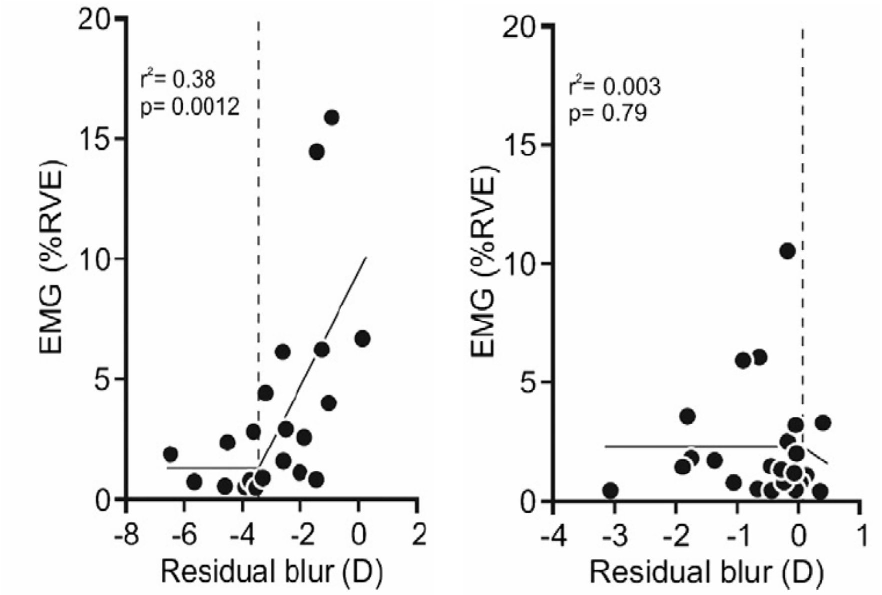

Fig. 5. Normalised trapezius median EMG levels during sustained accommodation/vergence to the target seen through: (Left panel) -3.5 D (Neg-Near), (Right panel) ±0 D (No-Blur). The cut-off values used in the bitwise linear regression analysis (stippled reference line) were fixed and equal to the specific amount of defocus blur induced via the optical trial lenses in the four 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. (Reprinted from Richter, H. O. *et al.*, 2010, Vis. Res., 50, 2559, with permission from Elsevier).

oculomotor near-work problems (i.e. asthenopia) may react in different ways to experimental conditions of oculomotor load and defocus blur [34, 35], two different categories of subjects were also included in the ECG analyzes; healthy symptom-free subjects and subjects with a history of eye disorder and neck disabilities. These analyzes were conducted to verify that the trap.m. activity was not caused by ANS arousal. The subjective experience of task difficulty could cause the trapezius muscle EMG to increase and co-vary with accommodation/vergence responses to nullify the trial-lens-induced blur [36, 37] (another reason for recording the ECG was to facilitate filtering of heart signal disturbances in the EMG signals). In this analysis, HR, HR_{std}, and LF/HF were used as markers of autonomic reactivity [38].

The analyses of the ECG recordings showed that the eye/neck-scapular area interactions formed in the Richter *et al.* [18, 33] studies did so in the absence of ANS mediation. The heart rate was significantly higher during eye-lens accommodation on the LED target (on average 71.2 beats per minute, bpm) than during a baseline consisting of eyes-closed rest (69.1 bpm), while the difference in the heart rate variability parameter HR_{std} was close to significant. None of the tested parameters, HR, HR_{std} or LF/HF ratio, was significantly affected by the experimental conditions or the repetition of the manipulation over time. As illustrated in Fig. 6, HR_{std} was slightly but significantly lower at baseline and fixation for the patient group in comparison to the symptom-free group. Since previous studies have shown that HRV measurement is useful in evaluating the mental health of normal subjects, the lower HRV response in the symptom group may be attributed to relatively more anxiety [39]. However, in the context of chronic muscle pain as a stress related-illness, it has been proposed that a constant state of physiological arousal may lead to exacerbation and maintained symptoms such as pain, functional disability and fatigue [40]. Hence, the lower HRV response in the symptom group may, more fundamentally, be a key mediating cause behind their distressing or debilitating pain in the eye-neck and/or scapular area [30].

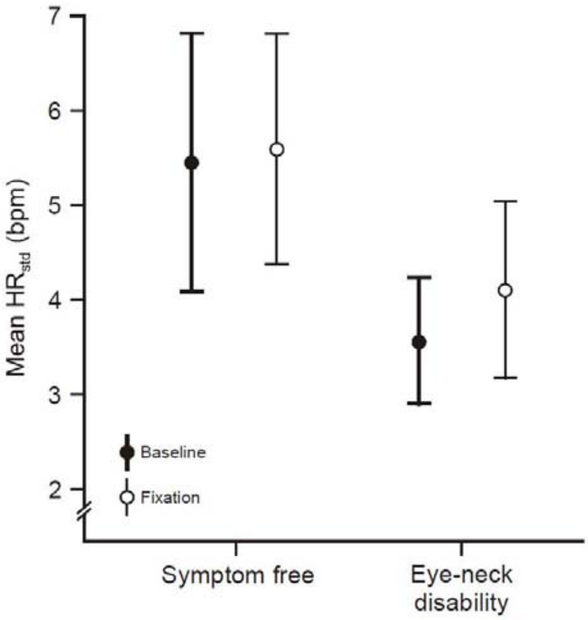

Fig. 6. Heart rate variability, in HR_{std}, for the patient and symptom-free groups of study participants. Error bars mark 95% confidence range.

Electrociliogram

One often neglected shortcoming inherent in most of the eye-lens accommodation measurements reported in the literature, including those reviewed here, is that “only” indirect measures of ciliary muscle function (i.e. accommodation of the crystalline eye-lens rather than accommodation of the ciliary muscle itself) have been obtained. Obviously this is a pragmatic choice since there have been very few other options (but see [41, 42, 43]). The choice of methodology nevertheless has implications, namely that potentially asthenopia-inducing changes in ciliary muscle activity, during or after sustained and strenuous near work, may largely go by unnoticed. More specifically, if the CNS elicits extra efferentation to the ciliary muscle e.g. in order to compensate for an uncorrected hyperopia or due to nervous tension and stress (which may impact on accommodative responsiveness), then the retinal image will not be compromised and the optometric measurements will hence not detect a change in pre-motor control processes despite the fact that such changes occurred. An imbalance (incongruent activation) may nevertheless result within the accommodation/vergence system which could give rise to symptoms and/or neck/scapular area linkages. This shortcoming can only be alleviated with direct measurements of the ciliary muscle itself.

Mechanisms subservient to gaze stabilization

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 has been observed in several independent studies to be strongly coupled to a bilateral increase in trapezius muscle activity [18, 33, 44]. The motor commands to the two effectors appear to be parallel, simultaneous and complementary, i.e. they produce different mechanical effects on different anatomical structures, effects that converge in obtaining the composite result of bringing the image to focus. The static 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 of the extraocular and neck and scapular muscles as well [20, 22, 45]. See Fig. 7.

The aforementioned eye-neck/scapular muscle activation linkages formed during accommodation/ vergence eye movements may alternatively emerge in a way which is similar to how the CNS compensates for ordinary every-day head movements. To be able to compensate for head movements and to induce correct stabilizing eye movements, the CNS integrates sensory information from the vestibular, visual and proprioceptive sensory organs. Then, with an extremely short latency, the CNS induces a close to perfect amount of innervations to the extraocular muscles to rotate the eye to move the retina with the same amount of displacements as the image motion. More specifically, neural integration and alignment of parallel streams of sensorimotor afferentation occurring in neural networks located in part in cerebellum may constitute a complementary explanatory scheme for trapezius muscle activity triggered by eye-lens accommodation [cf. ref. 19]. Foveal/ peripheral attention systems, neck/scapular area and accommodation/vergence muscles may become interconnected into one emergent supra-system for gaze control when the demands placed

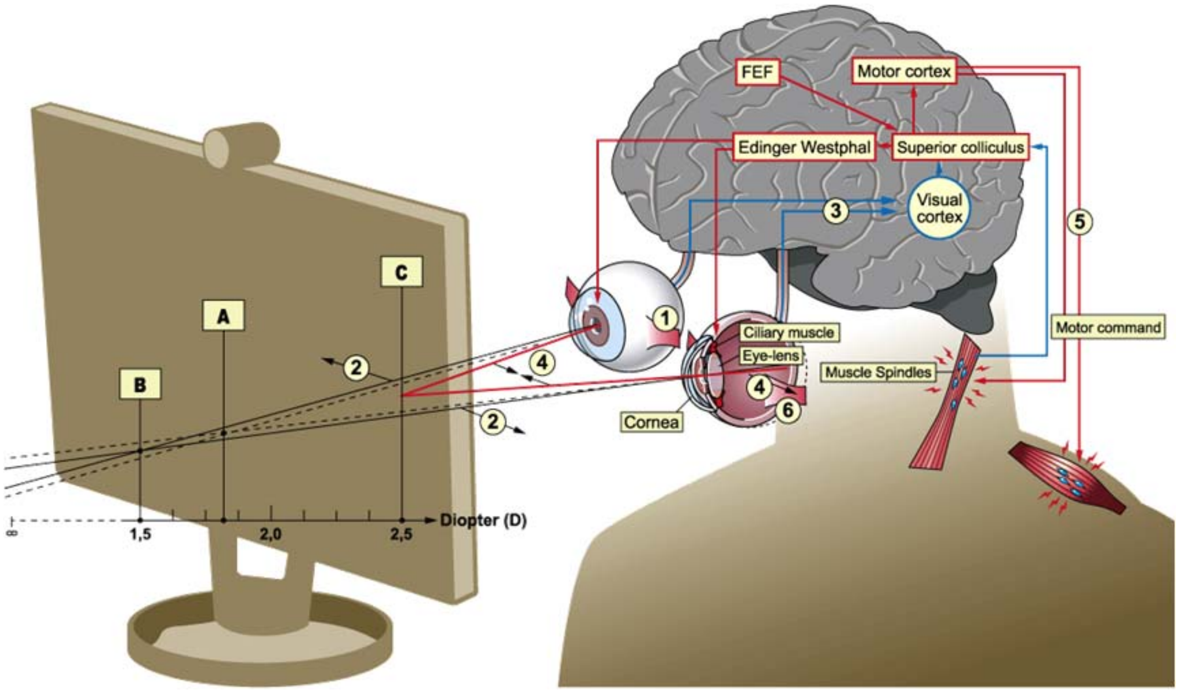

Fig. 7. Summarizing a theoretical account of visuomotor loops thought to underlie gaze stabilization, the figure shows tentatively central nervous system reflexes which may be activated during normal viewing conditions and, as reviewed here, when an accommodative/vergence foci (A) fatigues following strenuous near work and as a consequence temporarily dissociates into either a fatigued convergence foci (B) or a fatigued accommodative foci (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, resulting in blur and/or double vision in the retinal image (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, which makes 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. The end result achieved may be "too much" gaze stabilization. Evidence for interactions between the eye-movement system and accommodation has also emerged on the single unit level of analysis. Ohtsuka and Sato [25] demonstrated monosynaptic connectivity between omnipause and accommodation neurones within the rostral superior colliculus. Omnipause neurons in superior colliculus are tonically active in all periods of fixation and pause during saccades. Ohtsuka & Sato [25] also showed elicitation of accommodative responses by low-current stimulation of the rostral-portion of the superior colliculus corresponding to the representation of the central visual field. 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, may give rise to a broad spectrum of musculoskeletal problems and disorders when accumulated over time. (Reprinted from Richter, H. O. *et al.*, 2010, Vis. Res., 50, 2559, with permission from Elsevier).

on the accommodation/vergence system reach a certain threshold. The trigger to such synchronized activations may be speculated to come from e.g. the ciliary muscle efference copy. However, since the ciliary muscle recently was shown to have its own proprioceptors, the trigger signal, which activates the attention/postural system, may alternatively be supplied by afferentation [3].

Regardless of which one it is, according to this complementary scheme, alignments may occur according to the most prominent internal source of information, which under the experimental conditions reviewed here is the ciliary muscle [19, 46]. At present there is clearly a general lack of scientific information available when it comes to these underlying mechanism(s).

Nevertheless, it can be concluded that adjustments of eye-lens accommodation to the blurred target activate a postural stabilization process that uses the eye-neck/scapular area muscles to ensure that the target is held in the retinal area of highest visual acuity. This is because visual targets 1 deg or further away from the fovea constitute inadequate sensory stimuli to elicit or drive a well functioning accommodative response [47, 48]. Campbell [47] 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. To stabilize the retinal images, functional (hard-wired) neck/scapular muscle area action 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. Binocular vision, the result of gaze stabilization, notably also offers several advantages for the control of reaching and grasping [49]. Binocular disparity processing in particular has been mentioned as an important control variable in prehension movements.

Translational research with a focus on musculoskeletal disorders

Voluntary or reflexive accommodative/vergence effort may, as an unwarranted consequence, cause a dysfunctional tonus increase and/or reduced load variation in the neck, scapular area muscles and upper back. Through this eye-neck/scapular area functional linkage, sustained eye-lens accommodation at near distance may increase muscle activity above rest levels. The issue of temporal variability is of great interest in this context and to research in musculoskeletal disorders in general, as lack of variation in postures and muscle loads is generally accepted to be an important determinant of risk [50, 51]. The physiological mechanisms for development of symptoms from the neck and scapular area region are not yet fully understood. Several explanation models have been suggested. One of them, the so called Cinderella hypothesis, is based on a prescribed motor units recruitment and de-recruitment size-principle order; small low threshold motor units are recruited first and de-recruited last (constantly busy, like Cinderella). An overuse of the fibres belonging to these units may cause metabolic disturbances and exhaustion, which starts degenerative processes and pain. To avoid such overuse, according to the models, periods of total muscle relaxation are needed. Thus, a low increase of muscular activity above the rest level, which may be generated by oculomotor effort (e.g. due to an uncorrected visual error or deficient visual ergonomics), would substantially increase the risk for a continuous activation of motor units, and thereby contribute to overload and pain generation. Once the pain presents itself, other mechanisms come into play which in turn leads to increased muscle activity [30].

Important issues for future research include elucidating how the gaze stabilization response is distributed to different muscles. The trapezius muscle, which has received the most attention so far, is one muscle out of approximately two dozen that operate to stabilize the head/neck-scapulae and/or move it to adequate postures. Even though the link between visually demanding work and postures and loads on the neck/scapular region is generally accepted, the majority of the literature concerning accommodation/vergence control arises from experiments in “head-fixed” (i.e. paralyzed, anesthetized or immobilized) animals and humans. Functional fusion between the two systems can only be studied under conditions where the head is allowed to move freely. The eye-neck/scapular area link has so far been conceptualized as a relatively quick “reflex”, i.e. when the activity of the ciliary muscle is increased, the activity of the neck/scapular muscles also increases and with a minimal lead time. This has proven to be an overly simplistic view and the temporal patterning of the eye-neck/scapular area association therefore needs to be investigated. Another related issue is whether the link is completely automatic and involuntary.

Relationships should finally be established between the laboratory models of eye-neck/ scapular area interconnectedness and findings from the clinic [52] epidemiology [53, 54]. Although still in their infancy, such translational studies have started gaining attention recently.

CONCLUSION

In sum, considering the scant knowledge of the mechanisms controlling ocular accommodation/ vergence and their neglected role as a putative causal factor in musculoskeletal problems it appears appropriate to test and develop techniques for the study of the human ocular focusing process in this context. A new look on dysfunctional eye-head-neck-scapular interactions in occupational settings may be important for several interrelated reasons. It has proved difficult to establish a quantitative relationship between physical loads and the prevalence or incidence of shoulder neck complaints in workers with low static load levels. Different models have been suggested to explain the relationship between load and musculoskeletal symptoms from the neck and scapular area region. While a close relationship between visual demands and activation of the trapezius muscle seems plausible, the specific role of a neurophysiologic link has not been addressed in the discussion of risk factors underlying work-related musculoskeletal disorders.

ABBREVIATIONS

BA	:	Broadman area
bpm	:	beats per minute
CNS	:	Central Nervous System
D	:	dioptre. The reciprocal of viewing distance inmeters so that 1 dioptre corresponds to 1m, 2 dioptres corresponds to 0.50 m, etc.
ECG	:	Electrocardiography
EMG	:	Electromyography
HR	:	Heart rate
HR_{std}	:	standard deviation of heart rate
LF/HF ratio:		low frequency/high frequency hear rate ratio
PET	:	Positron Emission Tomography
rCBF	:	regional cerebral blood flow
RMS	:	Root mean square
RVE	:	Reference voluntary electrical activity

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REFERENCES

1. Gilmartin, B. 1986, Ophthalmic Physiol. Opt., 6, 23-37.
2. Gilmartin, B. 2000, Pharmacology of accommodative adaptation. In Franzén, O., Richter, H., and Stark, L. (Eds.), Accommodation/Vergence Mechanisms in the Visual System. Birkhauser-Verlag, Basel, 141-150.
3. Flügel-Koch, C., Neuhuber, W. L., Kaufman, P. L., and Lütjen-Drecoll, E. 2009, Invest. Ophthalmol. Vis. Sci., 50, 5529-36.
4. Davies, L. N., Wolffsohn, J. S., and Gilmartin, B. 2009, Ophthalmic Physiol. Opt., 29, 427-35.
5. Vasudevan, B., Ciuffreda, K. J., and Gilmartin, B. 2009, Invest. Ophthalmol. Vis. Sci., 50, 114-20.
6. Vilupuru, A. S., Kasthurirangan, S., and Glasser, A. 2005, Vision Res., 45, 181-91.
7. Ciuffreda, K. J. 1998, Accommodation, the pupil, and presbyopia. In Benjamin, W. J. (Ed.), Borish’s Clinical Refraction. W. B. Saunders Company, 77-120.
8. Franzén, O., Richter, H., and Stark, L. (Eds.) 2002, Accommodation/Vergence Mechanisms in the Visual System. Birkhauser-Verlag, Basel.
9. Semmlow, J. L. and Hung G. K. 1980, Am. J. Optom. Physiol. Opt., 57, 559-65.
10. Zhang, H. and Gamlin, P. D. 1998, J. Neurophysiol., 79, 1255-69.
11. Mays, L. E. and Gamlin, P. D. R. 1995, Cur. Opin. Neurobiol., 5, 763-768.

12. Richter, H., Lee, J. T. and Pardo, J. 2000, European J. Neurosci., 12, 311-321.
13. Posner, M. I. and Raichle, M. E. 1994, Images of Mind, Scientific American Library, New York.
14. Rockland, K. S. and Van Hoesen, G. W. 1994, Cerebral Cortex., 4, 300-313.
15. Ullman, S. 1995, Cerebral Cortex., 1, 1-11.
16. Heinze, H. J., Mangun, G. R., Burchert, W., Hinrichs, H., Scholz, M., Munte, T. F., Gös, A., Scher, M., Johannes, S., Hundeshagen, H., Gazzaniga, M. S., and Hillyard, S. A. 1994, Nature, 372, 543-546.
17. Motter, B. C. 1993, J. Neurophysiol., 70, 909-919.
18. Richter, H. O., Bänziger, T., Abdi, S., and Forsman, M. 2010, Vis. Res., 50, 2559-2569.
19. Richter, H. O. Costello, P., Sponheim, S. R. Lee, J. T., and Pardo, J. V. 2004, European J. Neurosci., 20, 2722-2732.
20. Richter, H. O., Andersson, J., Schneider, H., and Långström, B. 2005, European J. Neurosci., 21, 3077-3088.
21. Colebatch, J. G., Deiber, M. P., Passingham, R. E., Friston, K. J. and Frackowiak, R. S. 1991, J. Neurophysiol., 65, 1392-1401.
22. Corneil, B. D., Munoz, D. P., Chapman, B. B., Admans, T., and Cushing, S. L. 2008, Nature Neuroscience, 11, 13-15.
23. Sparks, D. L. 1999, Curr. Opin. Neurobiol., 9, 698-707.
24. Sawa, M. and Ohtsuka, K. 1994, Vision Res., 34, 975-981.
25. Ohtsuka, K. and Sato, A. 2000, In Franzén, O., Richter, H., and Stark, L. (Eds.), Accommodation/Vergence Mechanisms in the Visual System. Birkhauser-Verlag, Basel, 21-30.
26. Muller, J. R., Philiastides, M. G., and Newsome, W. T. 2005, Proc. Natl. Acad. Sci. USA, 18, 524-529.
27. Tu, T. A. and Keating, E. G. 2000, J. Neurophysiol., 84, 1103-1106.
28. Rasmussen, T. and Penfield, W. 1947, Res. Pub. Assoc. Res. Nerv. Mental Dis., 27, 346-361.
29. Guitton, D. and Mandl, G. 1978, Brain Res., 149, 313-327.
30. Johansson, H., Windhorst, U., Djupsjöbacka, M., and Passatore, M. (Eds.) 2003, Chronic Work-Related Myalgia. Neuromuscular Mechanisms Behind Work-Related Chronic Muscle Pain Syndromes. Gävle, Sweden.
31. Simons, D. J. 1943, Research Publications - Association for Research in Nervous and Mental Disease, 23, 228-244.
32. Lie, I. and Watten, R. 1987, European J. Physiol., 56, 151-156.
33. Richter, H. O., Bänziger, T., and Forsman, M. 2011, European J. Applied Physiology, 111, 29-36.
34. Treaster, D., Marras, W. S., Burr, D., Sheedy, J. E., and Hart, D. 2006, J. Electromyogr. Kinesiol., 16, 115-24.
35. Strøm, V., Røe, C., and Knardahl, S. 2009, Pain, 144, 147-55.
36. Friedman, B. H., Thayer, J. F., and Tyrrell, R. A. 1996, Clin. Auton. Res., 6, 147-152.
37. Davies, L. N., Wolffsohn, J. S., and Gilmartin, B. 2009, Ophthalmic Physiol. Opt., 29, 427-35
38. Task Force 1996, Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology Circulation, 93, 1043-65.
39. Shinba, T., Kariya, N., Matsui, Y., Ozawa, N., Matsuda, Y., and Yamamoto, K. 2008, Psychiatry Clin. Neurosci., 62, 603-9.
40. Passatore, M., and Roatta, S. 2006, European J. Applied Physiol., 98, 423-449.
41. Jacobson, J. H., Romaine, H. H., Halberg, G. P., and Stephens, G. 1958, Am. J. Ophthalmol., 46(5 Part 2), 231-8.
42. Swegmark, G., and Olsson, T. 1968, Acta Ophthalmol. (Copenhagen), 46, 946-68.
43. Forsman, M., Jansson, U., Lindström, S., Brautaset, R., Nilsson, M., Lodin, C., and Richter, H. 2011, Direct measurements of ciliary and trapezius muscle activity. Abstract accepted for paper presentation at 43rd Annual Nordic Ergonomics Society Conference (NES 2011).
44. Lodin, C., Forsman, M., and Richter, H. 2011, Sustained periods of ocular load may affect trapezius muscle activity. Abstract accepted for paper presentation at 43rd Annual Nordic Ergonomics Society Conference (NES 2011)
45. Corneil, B. D., Olivier, E., and Munoz, D. P. 2002, J. Neurophysiol., 88, 2000-2018.
46. Block H. J. and Bastian A. J. 2011, J. Neurophysiol., Apr 13 [Epub ahead of print].

47. Campbell, F. W. 1954, J. Physiol., 123, 357-366.
48. Gu, Y. C. and Legge, G. E. 1987, Journal of the Optical Society of America A. Optics and Image Science, 4, 1681-1687.
49. Melmoth D. R. and Grant S. 2006, Exp. Brain Res., 171, 371-88.
50. Mathiassen, S. E. 2006, Appl. Ergon., 37, 419-427.
51. Wells, R. H., Mathiassen, S. E., Medbo, L., and Winkel, J. 2007, Appl. Ergon., 38, 733-744.
52. Zetterström, C., Lundqvist, L.-O., and Richter, H. 2009, J. Optometry, 2, 127-133.
53. Wiholm, C., Richter, H. O., Mathiassen, S. E., and Toomingas, A. 2007, Scandinavian J. Work Environ. Health, Supplements, 3, 54-59
54. Richter, H., Zetterström, C., and Lundqvist, L.-O. 2011, Logistic regression analysis of eye-and-neck/scapular area interactions during visually deficient computer-work. Work, 39, 67-78.