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Accommodation–vergence performance after low levels of oculomotor load

by Hans O Richter, PhD,[1] Albert G Crenshaw, PhD,[1] Eugene Lyskov, PhD[1]

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Objectives This experimental pilot study assessed the effects of sustained low-level accommodative vergence loads on oculomotor performance, eyestrain, and musculoskeletal functioning.

Methods A high-contrast fixation-point stimulus [light-emitting diode (LED)] was introduced into the optical axis of the viewing eye or into the midline in case of binocular viewing. The participants (N=6) were asked to compensate for the blur incurred by adjusting the strength of their eye lens. The participants performed in the following three standardized sequential viewing tasks: (i) resting with eyes open in darkness, (ii) accommodating alternately on a near versus a far LED illuminated sequentially (near–far response), and (iii) sustained fixation upon a LED at near. After the third task, the first and second tasks were repeated once.

Results The main effects of the third task were to decrease the overall rate of binocular accommodative relaxation time (diopters/s) in the repetition of the second task trial. The baseline shifts in individual response times also correlated with changes in the response amplitudes under the binocular stimulus conditions, which required contraction of the ciliary muscle.

Conclusions The results taken as a whole validate a technique of essential interest to applied vision research.

Key terms accommodation; asthenopia; computer work; defocus; musculoskeletal discomfort; near work.

If an object of regard falls outside a viewer's 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 humor, 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. In order to provide clear and comfortable vision during professional computer work, the full integrity of the accommodation–vergence system is of crucial importance.

Many studies have demonstrated temporary changes in oculomotor function, such as recession of the near point of accommodation and convergence, delayed rates of accommodation, shifts in accommodation towards the resting point, changes in muscle balance, and induced myopia after professional work at a computer station. Many scientists have also found positive correlations between eyestrain and near work and also raised concerns about the medium- and long-term effects. Lie & Watten (1) found a variation in oculomotor load (ie, the amplitude of accommodation–vergence or the force of contraction of the ciliary muscle) by combining an alteration in visual distance and an application of minus lenses and consequently reported increased electromyographic activity in different muscles in the head, neck, and shoulder region. Aarås et al (2–4) and Horgen et al (5) have reported a correlation between visual discomfort and pain in the neck and shoulder. This observation was attributed to the extraocular muscles being in a state of static stress to prevent fatiguing muscles to produce disturbing double vision and to the reflex optic paths being at the origin of not only the ocular responses, but also of the responses of the extraocular and neck muscles (6). The exact relationship between oculomotor load, eyestrain, and musculoskeletal discomfort in healthy normal participants still remains elusive, however.

The subject of inquiry in this context is to identify particular sensations of eyestrain and musculoskeletal discomfort experimentally with low levels of oculomotor load. To verify that accommodation is loaded, it is informative to employ objective optical measurement techniques. The technique of photorefraction is unique in this sense, in being able to measure the dynamics of the ocular accommodation remotely and objectively in both eyes simultaneously. This pilot study sought to begin to explore the effects of low-level sustained loads in this regard. Musculoskeletal discomfort and symptoms of

1 Centre for Musculoskeletal Research, Gävle University, Gävle, Sweden.

Correspondence to: Hans Richter, Centre for Musculoskeletal Research, University of Gävle, 801 76 Gävle, Sweden. [E-mail: hrr@hig.se]

eyestrain were characterized before and after different levels of monocular or binocular accommodation–vergence loads. The levels of dioptric load actually obtained, as well as a specification of the consequences of such loads on oculomotor functioning, trapezius electromyographic activity and electrocardiographic activity, was quantified in parallel. Under experimental conditions of sustained negative and positive dioptrical blur, the participants were requested to compensate for the defocus incurred by altering the strength of their crystalline eye lens by means of accommodation–vergence eye movements.

Study population and methods

Study population

Six persons (5 women and 1 man), naïve and unpracticed students with a mean age of 31 (range 20–37, SD 6) years, were included in the study. The participants were recruited from the academic quarters of the University of Gävle and surroundings. All but one of the participants had taken part in a recent study (7). Eye examination data were available from five participants. The study followed ethical committee guidelines, and informed consent was given by each participant before they took part in this study. The participants received a monetary reward upon completion of the study. The study was approved by the Uppsala University Medical Ethical Review Board.

Eye examination

The goal of the optometrical examination, which included measures of acuity, motility, stereopsis, retinal correspondence, and fusion, was to prevent the inclusion of eye disease. All of the participants had normal, unaided, or aided acuity with no history of eye disease. The near points for both the accommodation and convergence functions were normal. Motility was normal. The difference between habitual correction and retinoscopically measured refractive errors was negligible (<0.5 D) in all cases. Pupil size and stereopsis at near and far distances were normal. Negative relative accommodation (mean 1.75, range 1.25–2.0, SD 0.43) and positive relative accommodation (range 2.25–3.75, mean 2.83, SD 0.80) were, on the average, within a range considered normal.

Visual and musculoskeletal discomfort

The degree of eyestrain and musculoskeletal discomfort experienced prior to and immediately after engagement in the experiment was assessed on a 16-point Borg scale ranging from no fatigue at all to extreme (maximum) fatigue (8). Differential symptom descriptors were used in an attempt to distinguish between different afferent pathways for the symptom of asthenopia. The internal symptom factors comprising "eyeache", "eyestrain", and "headache localized behind the eyes" have been related to accommodation–vergence stress (9). External symptom factors, including "irritation", "burning", and "dryness", are more associated with anterior ocular surface-inducing conditions. Prior to the start of the experiment, all of the participants were symptom free.

Methods

The experiment was carried out in a neutrally designed and windowless climate chamber measuring 3.9 m × 3.8 m × 2.5 m, with a controlled air temperature of 21°C. All of the measurements were completed in darkness and within <1.5 hours. The participants' heads were positioned in a chin rest. Both underarms and hands rested palm down immediately on a table, the horizontal surface of which was adjusted to a lower chest level in order to provide support and comfortable armrest. The high contrast polychromatic LED (light-emitting diode) targets (Everlight Electronics Inc, England) emitted a white color and were positioned in front of the participants in the midsagital plane in the case of binocular viewing or in the optical axis of the single viewing eye. The fixation-point stimulus LED subtended 3.66 degrees at the 7.8-cm (12.8 D) viewing distance and 0.32 degrees at the 0.9-m (1.1 D) distance, respectively. All of the participants used their dominant eye during the monocular viewing. The fellow nondominant eye was fully occluded. Varying magnitudes of defocus blur, +1.50, –0.25, –1.0, and –3.0 diopters (D), were introduced into the optical axis of the viewing eye(s). The lenses were mounted in trial frames (Oculus Inc, Dutenhofen, Germany). The participants were asked to compensate for the blur incurred by reflexively or voluntarily adjusting the dioptric strength of their crystalline eye lens (figure 1).

The participants performed the following three standardized sequential viewing tasks adapted from Richter et al (10): (i) resting with eyes open in darkness (REST), (ii) accommodating alternately on a near versus a far LED illuminated in 13 sequential epochs [near–far response (NFR)], and (iii) sustained steady-state foveal fixation upon a LED close to the age-appropriate near point of accommodation (FIX). In REST, the participants were instructed to "gaze straight ahead into the distance". In this condition a warm mirror filtered out virtually all visible light (while the participant's eye was aligned with the measurement axis of the optometer) allowing data acquisition from a resting (sensory open loop) viewing condition.

In the NFR condition, a step target was presented with the near LED 5 D away from the age-appropriate

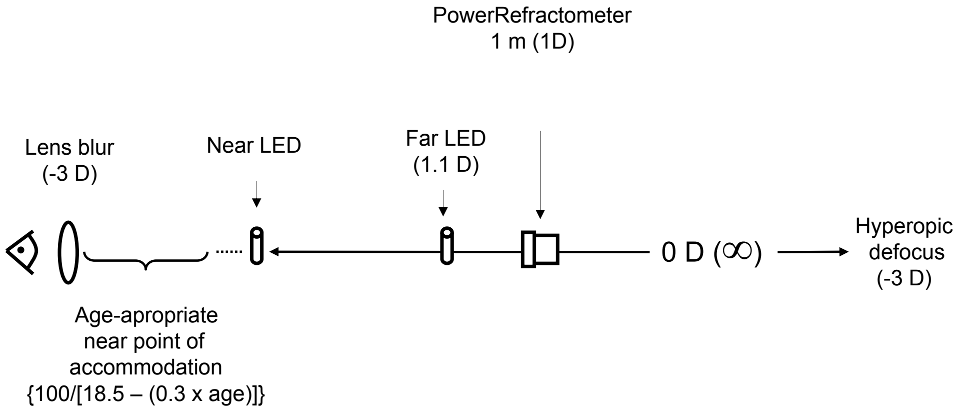

Figure 1. The LED (light-emitting diode) stimulus, which emitted a white color, was placed near the age-appropriate near point of accommodation (11). The far LED was placed at 1.1 D. The LED stimuli were observed monocularly or binocularly under various levels of defocus blur, which changed from trial to trial in a counterbalanced manner. The stimulus diopters (D) constituted a combination of the dioptric magnitude of the LED stimuli and the dioptric magnitude of the accommodation–vergence eyelens response requested to nullify the trial lens. The instructions to the participants were to "carefully focus on the LED target so that it is maximally sharp and clear at all times—maintain fixation." Objective measures of compensatory accommodation–vergence changes of the crystalline eye lens, to "nullify" the effect of the trial lens, were obtained by the PowerRefractometer.

near point of accommodation and the far LED at 0.9 m (1.11 D). The expected amplitude by age (in years) was calculated using Hofstetter's (11) equation {100/[18.5 – (0.3 × age)]}. Placement of the near LED, in the case of a 20-year-old participant (expected near point at 12.5 D or 8 cm) was accordingly calculated to be 7.5 D (13.3 cm). This stimulus setup was chosen to avoid unrealistically large stimulus magnitudes. Each LED was lit for a variable duration (between 1.2–2.5 seconds) in order to minimize the occurrence of predictive eye movements.

In FIX, the LED exhibited a "just noticeable dimming" at predetermined times to control visual attention and to help to posture accommodation onto the target. The instructions used during both NFR and FIX were modified from Richter et al (12): "carefully focus on the LED target so that it is maximally sharp and clear at all times—maintain fixation."

After the FIX period, both the REST and the NFR tasks were repeated once more. The order of the experimental blocks of monocular or binocular viewing was counterbalanced.

Apparatus

The accommodation–vergence response was assessed using an infrared video refractor (PowerRefractor R 03, Plusoptix, Dortmund, Germany). The PowerRefractor is a relatively new infrared autorefractor based on the principles of photorefraction. 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. Because fixation can be monitored, it can be excluded that changes in refraction are off-axis refractive errors rather than accommodation. One limitation is that small pupils (which return little light) cannot be measured. The optometer operates with a minimum pupil of 2.8 mm and tolerates eye movements of ± 25 degrees from a central fixation (7). The PowerRefractor records spherical refraction at 25 Hz without compensation for the work distance (ie, an emmetropic or corrected eye focused on the plane of the PowerRefractometer at 1 m will register a sphere of 0 D).

Data processing

The PowerRefractor data were imported to a MATLAB 7.1 (MathWorks, Inc), where it was filtered with a rectangular 10-point moving average that included every 10th sample. Recordings outside of the linear range of the optometer and outliers were excluded. The refraction data from the participant's right eye was thereafter compared with stimulus diopters. The stimulus diopters constitute a combination of the dioptric magnitude of the LED stimuli and the dioptric magnitude of the accommodation–vergence eyelens response requested to nullify the trial lens. In order to render the refraction data into a format that allowed comparison with the stimulus diopters, the following steps were taken. First, the reference was shifted, from a default distance of 1 m to optical infinity (ie, to a reference that normally equals a minimum of load on the oculomotor system). This procedure was accomplished by subtracting one from all of the PlusOptix refraction data. The magnitude of the dioptric lens placed in front of the eye was thereafter subtracted from all of the data. In our experiment, lenses of varying plus or minus magnitudes were placed immediately in front of the eye(s), rendering the optometric output value more or less "myopic" or "hyperopic", depending on the degree to compensatory plus or minus accommodation. The ability to posture the accommodation–vergence response on the LED target in NFR and FIX also entered into these considerations. Therefore, the magnitude of the LED stimuli was also subtracted from the "lens-free" data (whereas the REST data was corrected only for the blur induced by the trial lens). The residual refraction values (ie, the degree to "error" or absence thereof) relative to the stimulus diopters, represented the response diopters.

The accommodation–vergence reaction time, rate of dioptric change per second, and the response amplitude was extracted from the NFR trials. The algorithm utilized to obtain these dependent measures first identified the maximum stable portion of the response trajectory in two 0.5-second time windows lying immediately adjacent to the step change in the stimulus diopters. The midpoint refraction value, between the start and stop values (in the in-flight course) was identified next. Originating from this reference, a linear fit was imposed on a selected number of samples immediately before and directly after this intermediate value. The temporal offset of the extrapolated upper portion of this estimated line, relative to the dioptric start value, constituted the reaction time. The slope of this function is the response time in diopters per second (D/s) (figure 2).

Electromyographic activity and electrocardiographic recordings

Electrical muscle activity was recorded bilaterally from the upper trapezius muscles using two pairs of self-adhesive surface silver/silver chloride electrodes with a center of 20-mm intraelectrode distance placed 2 cm lateral from the midpoint between the seventh cervical vertebrae and the end of the acromion. The signal was amplified, filtered 10–1000 Hz, and sampled at 2000 Hz. The electromyographic root-mean-square was assessed within nonoverlapped windows of a 100-ms duration.

Electrocardiography was recorded from the thorax derivation (midaxillary sixth left rib–distal sternum) with a 0.5–200 Hz bandpass and a 2000 Hz sampling rate. R-R intervals were detected by a special programmed script (Spike 6.01, Cambridge Electronic Design, United Kingdom). After visual inspection, artifacts free intervalograms were further analyzed in the time and frequency domain. Mean values and the standard deviation of normal interbeat intervals, spectral power in the low (0.04–0.15 Hz) and high (0.15–0.4 Hz) frequency bands were calculated.

Statistical analysis

Statistical analyses were performed in SPSS 13.0 for Windows (SPSS Inc, Chicago, IL, USA). Two-tailed Pearson correlation coefficients were computed between the stimulus diopters and the response diopters during the rest conditions with the eyes open in darkness (REST) and during the different levels of sustained oculomotor loads in FIX. Paired t-tests or Wilcoxon signed-ranks tests were used to test for differences in the response amplitude, reaction time, and slope (D/s) in the near-to-far trials pre- and post-FIX. To characterize the electrophysiological effects of FIX in each experimental lens condition, electromyographic and electrocardiographic variables were calculated separately in the following three 2-minute time windows: during REST-pre, during FIX, and during REST-post. Additional analyses investigated the effect of FIX on baseline shifts in eyestrain and the neck–shoulder discomfort ratings.

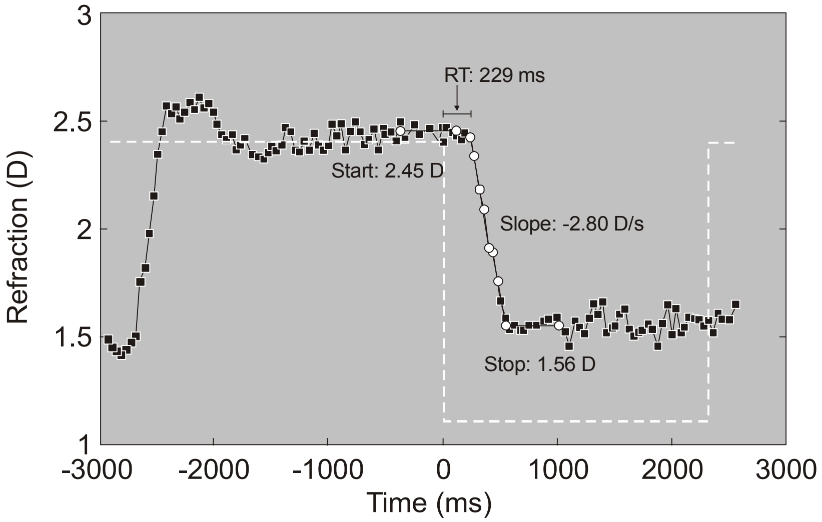

Figure 2. Diagrammatic representation of the stimulus and response parameters used to study the near–far response (NFR). One cycle of binocular near-to-far stimulation under the influence of +1 D is shown.

Results

Stimulus diopters versus response diopters

The group average magnitude of the binocular accommodative eyelens responses, to nullify trial lenses in FIX, was significantly correlated with the stimulus diopters (r_{xy}; x: stimulus diopters, y: accommodative response: 0.90, $P<0.001$). The group average magnitude of the data on the monocular accommodative response showed a similar outcome (r_{xy}; 0.91, $P<0.05$) (figure 3). The accommodation–vergence refraction data collected in darkness during the REST trials was uncorrelated with the stimulus diopters and, instead, regressed into an intermediate dioptric value exhibiting a grand average of 1.44 (SD 0.91) D. There were also no differences between the monocular or binocular REST values (figure 4).

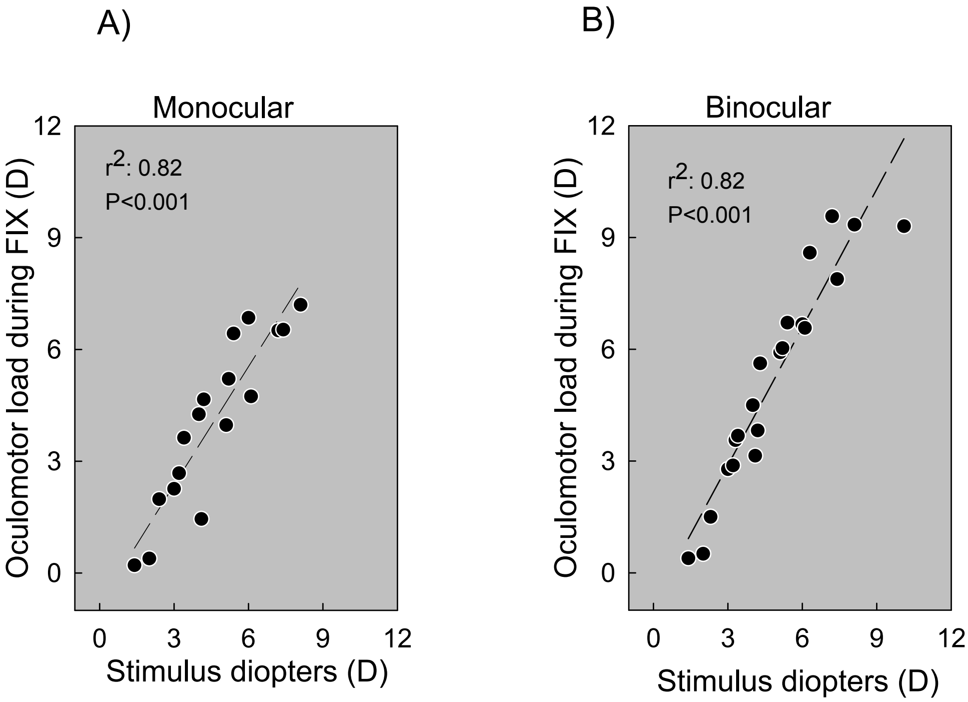

Figure 3. Test of the relationship between stimulus diopters versus response diopters during the sustained (2-minute) periods of alternating levels of steady-state foveal fixation upon a LED (light-emitting diode) at the age-appropriate near point of accommodation (FIX)—The data are group-averaged means. (A = monocular response, B = binocular response)

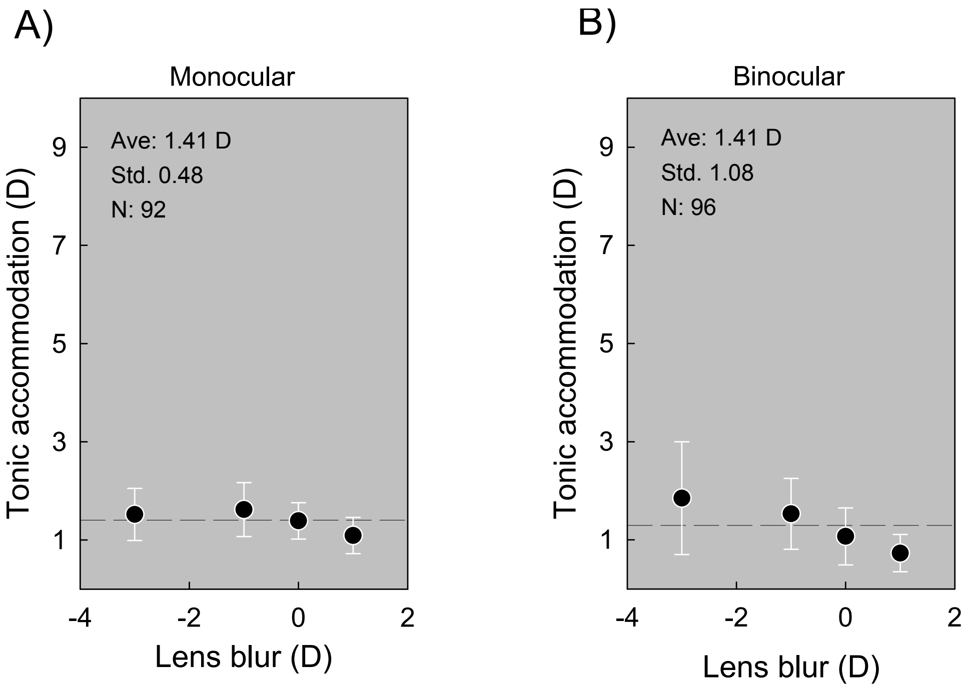

Figure 4. Test of the relationship between lens blur versus the group-average tonic accommodation response diopters (REST). Data are group-averaged means ± 1 standard deviation. In this condition the participants were instructed to gaze into the distance with their eyes open while the room was darkened. This stimulus arrangement allowed data collection from a resting (sensory open loop) condition. (A = monocular response, B = binocular response)

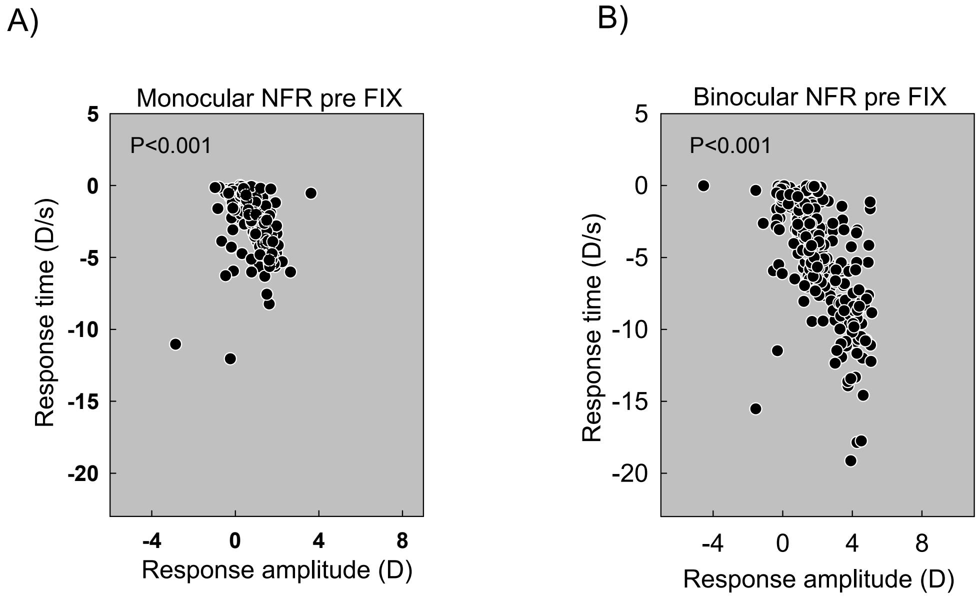

Figure 5. Pre-oculomotor load—test of the relationship between the accommodation–vergence response amplitudes versus the response times (D/s) during near-to-far stimulation (NFR). In this condition, a step target was presented, with the near LED (light-emitting diode) close to the age-appropriate near point of accommodation and the far LED at 0.9 m (1.11 D). Each LED was lit for a variable duration (between 1.2–2.5 s) in order to minimize the occurrence of predictive eye movements. Varying magnitudes of defocus blur, +1.50, –0.25, –1.0, and –3.0 diopters, were also introduced into the optical axis of the viewing eye(s). The data are values from individual trials. (A = monocular response, B = binocular response, FIX = alternating levels of steady-state foveal fixation upon a LED at the age-appropriate near point of accommodation)

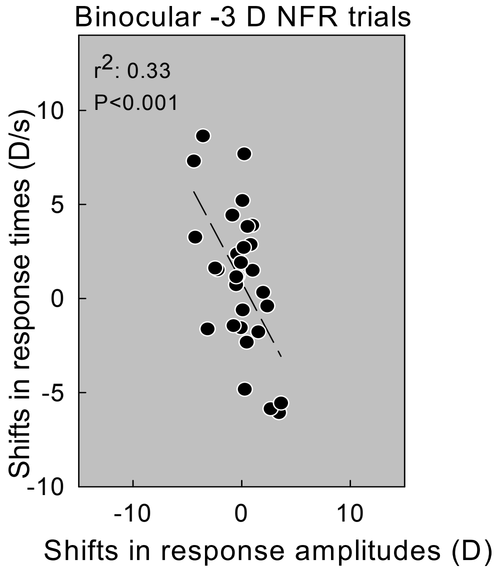

Figure 6. Postoculomotor load—test of the relationship between the response amplitudes versus the rates of dioptric change (D/s) pre–post FIX for binocular –3 D trials of defocus blur—the data are values from individual trials. [NFR = near–far response, FIX = alternating levels of steady-state foveal fixation upon a LED (light-emitting diode) at the age-appropriate near point of accommodation]

Near-to-far responses pre-FIX

The monocular reaction times averaged 520 (SD 528) ms, while the binocular reaction times averaged 422 (SD 475) ms. The response time averaged –5.16 (SD 3.67) D/s during the binocular trials, while the monocular response time averaged –2.48 (SD 2.05) D/s. The monocular response amplitudes averaged 0.75 (SD 0.74) D (abscissa, figure 5A). The binocular amplitudes averaged 1.74 (SD 1.44) D (abscissa, figure 5B). The individual response times correlated with the response amplitudes (P<0.001) (figure 5A–B).

Near-to-far response post-FIX

No systematic effect of FIX on the reaction times was evident in the NFR trials. In the binocular trials, a significant decrease in the overall response time occurred after FIX (P<0.05), from –5.16 (SD 3.67) D/s to –4.65 (SD 3.32) D/s. The binocular response time was reduced by an average of 0.50 (SD 3.77) D/s. No such effect was present in the monocular condition or for the response amplitudes (P>0.05). Baseline shifts in the individual response times and response amplitudes were correlated in the binocular stimulus conditions, which required contraction of the ciliary muscle [–1 D trials (P<0.05), –3 D trials (P<0.001)] (figure 6).

Absence of effects of FIX

No effect of FIX was evident on the refraction data recorded in darkness or on the trapezius EMG or heart rate variability (P>0.05). No effect of FIX was evident for eyestrain or the neck discomfort ratings (P>0.05).

Discussion

Accommodation–vergence eye movements in response to optical blur

The force of contraction of the ciliary muscle is of central interest in studies concerned with the issue of whether adjustments of accommodation–vergence in response to visual stress involve a centrally controlled eye–head–neck–shoulder motor program, the neural circuits that cause physiological levels of muscular tension in the neck and shoulder to covary with efference to the ciliary muscle (1, 6).

During FIX, an ideal observer, completely task-compliant and fully corrected or emmetropic, is expected to nullify the minus lenses through incremental eyelens adjustments. In addition, the steady-state accommodation–vergence response is expected to be postured close to the LED stimuli. This is generally what was observed by us. The refraction data showed a tight relationship to stimulus diopters under both binocular and monocular viewing conditions. The participant's level of oculomotor load was, in addition, verified to be stable because systematic drifts in the data were absent. Thus the force of contraction of the ciliary muscle (ie, level of load) increased during the act of accommodation. As the amplitude of accommodation increased, during minus blur, the force of contraction increased in direct proportion to the response amplitude (13).

With the use of formulas based on Duane's data (11), the maximum of the age-predicted (theoretical) near point for our volunteers was 7.93 cm or 12.6 D $\{100/[25 - (0.4 \times \text{age})]\}$. This value can be compared with the actual performance. The monocular amplitudes of accommodation–vergence throughout FIX averaged 26.3 cm or 3.8 D (SD 2.29). The binocular values averaged 20.4 cm or 4.9 D (SD 2.81). Hence the accommodation–vergence system was loaded by 30% of the maximum amplitude, on the average, during the monocular viewing and by 39% during binocular viewing. The actual near-point values should however be measured objectively in that accommodation may not be as sufficient as expected in professional workers with musculoskeletal discomfort or eyestrain. Reduced accommodative amplitude caused by visual stress during professional near-work in all likelihood acts to increase the force of contraction of the ciliary muscle.

Refraction in darkness pre-FIX

During low-luminance viewing conditions, in the absence of an adequate stimulus, accommodation adopts an intermediate focus referred to as the "resting position". The magnitude of the resting focus is known to be dependent on the concurrent balance between the parasympathetic and sympathetic innervation to the ciliary muscle. The magnitudes and the standard deviation of the individual resting focus values during the current open loop measurements are in close correspondence with earlier reported estimates. Leibowitz & Owens (14) reported an average resting focus of 1.5 D (66 cm) for 220 college students, with an SD of 0.75. This outcome constitutes an important measure of external validity for our data set and gives credence to the way the data were collected and analyzed.

Near-to-far response pre-FIX

The average reaction time to a nonrepetitive near-to-far target has been reported to be ~380 (SD 80) ms (15). The close similarity of this estimate to our participants' reaction times further underscores the external validity of our data. Peak accommodative velocity, which is a function of amplitude, is known to exhibit values of ≥10 D/s. Owing to the relatively small response amplitudes implicated in our NFR trials, the present response times appear physiologically plausible.

Effects of oculomotor load on near-to-far response

If the binocular response amplitudes narrowed after FIX, in the minus lens stimulus conditions, their maximum velocity would also be predicted to be lower due to the "main-sequence" neurological control of accommodation in which peak velocity is proportional to the accommodative response amplitude (15). Indeed this is what was observed by us.

Absence of effects of oculomotor load on the resting focus value

The absence of systematic baseline-shifts in the magnitude of the individual resting focus value can be attributed to the low levels of arousal of the autonomous nervous system during FIX. Behavioral links between the oculomotor and cardiovascular systems, a conceivable outcome of professional computer work (16), was therefore not addressed in our study. The absence of hysteresis in the tonic accommodation measures, a well-documented mechanical consequence of exaggerated near work, was probably due to the temporal order of the experimental phases. Most of the adaptation (part of which was actually observed in the NFR trials) dissipated during the end of the intervening NFR task (15).

Eyestrain and musculoskeletal discomfort

In all instances, after participation in the current experiment, the eyestrain and musculoskeletal discomfort ratings remained low (> very very weak symptoms or very weak symptoms). Hence, the eyestrain and musculoskeletal discomfort ratings converged to indicate that the effects of the investigated oculomotor levels of the loads were negligible with respect to symptoms of discomfort. However, it is important to realize that our participants were all young and healthy. Other study populations (eg, those afflicted by chronic work-related myalgia or professional oculomotor near-work problems), in all likelihood, would react differently, even to low or “moderate” levels of oculomotor load.

Future directions

The focal point of our study was on the methodological development of experimental techniques that allow well-defined levels of oculomotor load to be induced while task compliance is monitored objectively. The results convincingly show that the used photorefractor system, together with the used analytic techniques, are able to adequately capture important aspects of basic oculomotor processing, which are of essential interest to applied vision research. Additional methodological developments are needed, however, so that all relevant aspects of the near-triad can be included in future analyses (ie, pupilary and vergence system).

The weight of our evidence points to a discernible, yet complex connection between eye problems and neck and upper back complaints and is one that deserves further investigation. Further analysis of processing characteristics of the fine and individual structure of oculomotor, cardiovascular, and trapezius muscles for a longer duration and at larger amplitude levels of oculomotor load (than what was used by us) are however not only desirable, but necessary when it comes to the long-term objective to establish quantitative relationships between oculomotor levels of load, eyestrain, and neck and shoulder symptoms of discomfort. An important issue for future research, in this regard, will also be to disambiguate the question related to if “duration load” is interchangeable with “amplitude load” and the extent to which either consequences is additive or not.

Treaster et al (17) used the electromyographic-dependent variable cyclic changes in the median frequency to assess the development of trigger points in the trapezius muscle induced by low versus high visual and postural stress conditions during a computer task. The authors concluded that high visual stress may be a factor in the development of myofascial pain response. This and other studies thereby promote the use of electromyography in future studies using the novel experimental techniques tested in this study.

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