A Behavioral Link Between the Oculomotor and Cardiovascular Systems

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ABSTRACT—Although the eyes and the heart serve very different purposes, each receives autonomic innervation. Capitalizing on recent theoretical and technological innovations in the understanding and assessment of oculomotor and cardiovascular behavior, three experiments measured behavioral covariation between the oculomotor and cardiovascular systems. Measures of dark focus and dark vergence indexed oculomotor tone, and the spectral decomposition of variations in heart rate indexed cardiovascular control mechanisms. In Experiment 1, individual differences in cardiovascular parameters could predict individuals' dark vergence (R^2=.806) but not their dark focus (R^2=.404). In Experiment 2, the same parameters were measured from subjects who experience either panic attacks (n=11) or blood phobia (n=9). Heart rate was positively correlated with dark vergence and the two subject groups were separable based on both oculomotor and cardiovascular variables. Using a within-subjects approach, Experiment 3 found that both dark vergence and dark focus tended to be nearer during sympathetic dominance of the heart than during parasympathetic dominance, within-subjects variations in cardiovascular parameters could predict dark focus, and between-subjects variations in interbeat intervals could predict dark vergence. Shared patterns of autonomic activation may be responsible for this eye-heart link.

IT HAS LONG BEEN RECOGNIZED that the heart receives innervation from both the sympathetic and parasympathetic branches of the autonomic nervous system (ANS). Recent evidence suggests that this may also be true for the oculomotor systems that aid us in seeing clear and single images at different distances; accommodation (the oculomotor system mediating the focusing behavior of the ciliary muscles that control the shape and power of the intraocular lenses) and binocular vergence (the oculomotor system mediating convergent and divergent eye movements via the extraocular muscles). Since the cardiovascular and oculomotor systems serve very different purposes, some degree of independence would be expected. However, since each receives autonomic innervation and since they are exposed to similar internal and external conditions, it is possible that these systems do not function completely independently. The goal of this investigation was to determine if a behavioral link exists between the oculomotor and cardiovascular systems.

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This effort was prompted by recent theoretical and technological innovations in the understanding and measurement of tonic activity in both the oculomotor and cardiovascular systems. Consistent with these innovations, tonic activity in the cardiovascular system was indexed by variables derived from the spectral decomposition of the variability in heart rate. The oculomotor resting states—dark focus and dark vergence—indexed tonic activity in the visual system (Owens, 1984).

Oculomotor Resting States as Psychophysiological Variables

Substantial evidence exists for an autonomic control of accommodation. Accommodative changes have long been observed, for example, in subjects who were anxious, angry, or insulted (Cogan, 1937; Leibowitz, 1976; Miller, 1978; Miller & LeBeau, 1982; Westheimer, 1957). Interpreting these effects in terms of autonomic activity, however, is difficult due to the lack of other (simultaneous) psychophysiological measurements. Thus, although it is generally accepted that accommodation is influenced by changes in ANS activity, controversy regarding the underlying mechanisms remains.

Traditional (and largely discredited) theories of accommodation maintain that activation of the parasympathetic branch of the ANS leads directly to an increase in accommodation (i.e., a nearer focusing distance). According to this theory, when the system is at rest it surrenders to elastic forces and returns to the far point of its operating range (optical infinity for those individuals free of refractive error); no autonomic innervation is necessary to focus at far distances.

Modern anatomical, physiological, and pharmacological evidence suggests, however, that accommodation is innervated by *both* branches of the ANS (see Gilmartin, 1986, for a review of the evidence for sympathetic influences on accommodation). According to this dual-innervation theory, the accommodation system relaxes at and operates around a tonic position that corresponds to an *intermediate* distance (Owens, 1984). This tonic position can be measured in darkness, when there is no direct stimulus for accommodation, and has been variously called resting focus, tonic accommodation, and dark focus. The dual-innervation theory maintains that this tonic position is determined by a combination of the opposing sympathetic (β-adrenergic) and parasympathetic influences (e.g., Gilmartin, 1986; Gilmartin, Hogan, & Thompson, 1984; Miller & Takahama, 1988; Toates, 1972). Miller and Takahama (1988) measured dark focus while subjects experienced a wide variety of stimulus conditions. Consistent with dual-innervation theory, dark focus values were smaller (i.e., corresponding to a farther accommodative distance) in conditions that were expected to induce sympathetic activation (cold pressor stimulation, mental activity) than in conditions that were expected to induce parasympathetic activation (e.g., progressive relaxation, exposure to nature sounds). Subjects' ratings of "arousal" were consistent with this result—arousal ratings were negatively correlated with dark focus. No direct psychophysiological measurements were made, however, and some of the effects are paradoxical and difficult to interpret. When exposed to white noise, for example, Miller and Takahama discovered accommodative responses similar to that found during relaxation, in spite of the fact that the subjects rated the white noise condition as relatively arousing.

Binocular vergence is another oculomotor system that may reflect autonomic influences. Similar to accommodation, this system has been shown to have a resting state, measurable in darkness (dark vergence), that corresponds on average to an intermediate viewing distance (Owens & Leibowitz, 1983). Although the accommodation and vergence systems normally exhibit a large degree of synkinesis, the two systems dissociate in darkness; dark focus and dark vergence are not strongly related (e.g., Miller & Takahama, 1988; Owens & Leibowitz, 1976, 1980, Owens & Wolf-Kelly, 1987). Thus, it is possible that dark vergence provides an additional oculomotor variable with which to study autonomic influences (Owens & Tyrrell, 1992). Compared to the amount of research into autonomic influences on accommodation, there has been much less research into the possible role of the ANS in controlling vergence behavior. At least two pieces of evidence suggest, however, that the ANS is involved in vergence control. First, it is well known that physical pressure on the extraocular muscles stimulates parasympathetic activity and results in bradycardia (Alexander, 1975; Mallinson & Coombes, 1960). This reflex (known as the oculocardiac or trigeminovagal reflex) can be so powerful that without pharmacological intervention (e.g., atropine), cardiac arrest can result from ocular surgery. Although much is known regarding the mechanisms of this reflex, as well as its implications for ophthalmic surgery (Blanc et al., 1983; Gandevia et al., 1978), relatively little is known about the functional implications of this reflex for intact humans (Ebenholtz et al., in press). Second, Miller and Takahama (1988) found that dark vergence was significantly more distant (smaller dark vergence values) during relaxation than in other conditions and that ratings of "arousal" were positively correlated with dark vergence.[1]

Consistent with the notion of autonomic control of oculomotor behavior and the utility of oculomotor resting states as psychophysiological indices is the fact that dark focus and dark vergence exhibit large individual differences. The oculomotor resting states are the "set point" at which each system rests and operates around. Variations in dark focus and dark vergence have proven useful for understanding a wide range of visual phenomena including three dimensional space perception (Owens, 1987), previously anomalous myopias (Leibowitz & Owens, 1975a, 1975b; Owens, 1979; Post et al., 1979), and symptoms associated with close visual work (Jaschinski-Kruza, 1991; Owens & Wolf-Kelly, 1987; Tyrrell & Leibowitz, 1990). However, the physiological sources for the variations in dark focus and dark vergence remain largely unknown. An understanding of these variations and the possible role of the ANS in producing them would be useful on both theoretical and practical levels.

Spectral Decomposition of Heart Rate Variability

Although it has long been recognized that the heart is innervated by both the sympathetic and parasympathetic branches of the ANS, obtaining noninvasive indices of autonomic cardiac control has been complicated by this dual-innervation. For example, measures of heart rate confound the relative contribution of the two branches. By itself, an increase in heart rate could be attributed to either sympathetic activation, parasympathetic withdrawal, or both. Recently, however, research into the high degree of heart rate variability that exists in healthy individuals has yielded theoretical and technological innovations elucidating autonomic cardiac-control mechanisms. One relatively simple measure of heart rate variability, the standard deviation of interbeat intervals, is thought to be related primarily to tonic parasympathetic (vagal) functioning and has been linked to cardiovascular health (e.g., Kleiger et al., 1987; Martin et al., 1987; Thayer et al., 1991). More complex measures of cardiac variability have been shown to provide independent indices of sympathetic and parasympathetic influence. The spectral decomposition of heart rate variability consistently yields two components as the primary sources of variability—a low-frequency component (LF; approximately 0.1 Hz) and a high-frequency component (HF; approximately 0.25 Hz; e.g., Akselrod, et al., 1981). These components appear to have separate neural origins. While it is generally agreed that parasympathetic activity is responsible for the HF component (via respiratory sinus arrythmia), there is some disagreement regarding the source of the LF component (Saul, 1990). Although under certain conditions LF variations reflect significant parasympathetic influence (Saul, 1990), this component has been found to reflect primarily sympathetic activation (Pagani et al., 1992; 1993). These components are sensitive to psychological manipulations, as well as invasive and noninvasive physiological manipulations (Cerutti et al., 1988; Pagani et al., 1986; 1992; 1993). Recently Friedman et al., (1993) used parameters derived from the spectral decomposition of heart rate variability, along with more conventional cardiovascular indices, to describe autonomic patterns that distinguish two forms of anxiety. In contrast to a group of subjects who reported intense somatic reactions (including syncope) to the sight of blood, a group who reported severe and recent panic attacks exhibited an elevated heart rate, decreased heart rate variability, and relative sympathetic dominance of cardiac control.

The present experiments sought to determine whether measures of dark vergence and dark focus are related to measures of cardiovascular activity. Experiments 1 and 2 examined between-subjects effects. In Experiment 1, a regression model was used to determine whether cardiovascular parameters could predict individual differences in dark vergence and dark focus. Experiment 2 was conducted to determine whether oculomotor measurements could distinguish between two groups that have been shown to be cardiovascularly distinct. Finally, Experiment 3 examined within-subjects effects.

Experiment 1

Levy and Zieske (1969) established that heart rate could be successfully predicted by a regression model that included measures of the sympathetic and parasympathetic activation to the heart, the squares of these values, and a term describing their interaction. In this experiment, a similar regression approach was used to determine the extent to which individual differences in cardiovascular parameters could predict individual differences in dark vergence and dark focus. To obtain accurate indices of cardiovascular traits, cardiovascular behavior was monitored, and averaged across, a variety of situations that induced varying levels of sympathetic and parasympathetic activation (Manuck, 1994). A shock avoidance / reaction time task evoked sympathetic activity, a cold face stress evoked parasympathetic activity, and a third task, which combined shock avoidance with the cold face stress, evoked simultaneous sympathetic and parasympathetic activity.

Method

Subjects. Twelve healthy students (mean age = 20.8 years, standard deviation = 2.8 years) participated. All 12 exhibited a far binocular acuity of 20/35 or better without the aid of spectacles. Subjects provided their written consent prior to the experiment and were paid for their participation. All had agreed to abstain from caffeine, nicotine, and alcohol for at least 12 hours prior to the experiment. Due to equipment difficulties, accommodative data are not available for two subjects.

Apparatus. A Canon R-1 Autorefractor measured dark focus. This instrument provides valid and reliable objective measures of accommodation with a resolution of 0.12 diopter for both spherical and cylindrical lens powers (McBrien & Millodot, 1985). Less than one second is required for each measurement and, because it relies on infrared radiation, the instrument is operable in complete darkness. To control for astigmatic influences, all measures of accommodation were transformed into their mean spherical equivalent values by adding half the cylindrical power from the spherical power. Dark focus measures are expressed in diopters (D; the inverse of the accommodative distance expressed in meters). Thus, a greater dark focus value represents a nearer dark focus distance.

A "Vergamatic" (Steven Spadafore, Lancaster, PA) measured dark vergence. This is an automated device that assesses vergence through the subjective alignment of dichoptically presented light-emitting diode (LED) stimuli and is conceptually similar to a device described by Miller (1987). During measurement, a vertical column of six green LEDs is presented to the left eye for 100 msec while a single yellow LED (from a row of 128 spaced at 4 LEDs per cm) is presented to the right eye simultaneously. After each flash, the subject presses one of two response buttons to indicate whether the lone yellow LED appeared to the left or to the right of the green column. This process is repeated, using the Modified Binary Search procedure (Tyrrell & Owens, 1988) to determine which of the 128 yellow LEDs appears to the subject to be aligned with the column. Given the true distance from this LED to the column, the subject's interpupilary distance, and the distance from the subject's eyes to the Vergamatic, the vergence position can be computed. To facilitate comparisons between vergence and accommodation, vergence values are expressed in meter-angles (MA; the inverse of the distance in meters at which the two visual axes intersect). The Vergamatic was mounted above the autorefractor with its LEDs facing downward. The subject viewed the reflection of the LEDs from a partially silvered first surface mirror that had been mounted on the top surface of the autorefractor.

Electrocardiographic (ECG) recordings were obtained with Ag-AgCl electrodes with the impedance reduced to less than 10 Kohms using an abrasive skin preparation. One electrode was placed on the subject's left side between the ribs and hip, another at the same position on the right side, and a grounding electrode 2–5 cm directly beneath the latter. The ECG signal was amplified by a Grass 7P3 preamplifier and a Grass 7DA driver amplifier prior to being sampled by an analog-to-digital converter at 1 kHz. Systolic and diastolic blood pressure were monitored at 1 minute intervals with a SD-700A BP/Pulse monitor. Electrical shocks varied from 0 to 0.66 VAC and were delivered from a battery-operated Farrel Instruments Mark I Behavior Modifier through electrodes placed on the subject's right calf.

Procedure. The visual measurements took place in a separate laboratory from the other measurements, with the visual measurements always being made first. Five measures of accommodation in darkness were made. Subjects sat in total darkness for 2–3 minutes while the procedures were explained. The subject positioned his or her chin on the autorefractor's support and was told to relax and look straight ahead. To reduce the confound of refractive errors in measures of TA, five measures of accommodation were made while the subject was instructed to keep the image of a brightly illuminated far (6 m) high contrast acuity chart (Bernell, Inc.) in as sharp focus as possible. The mean of these measures was subtracted from the mean value measured in darkness to yield the measure of dark focus. Prior to measurement of dark vergence, the subject was given instructions and practice on the task. During measurement, the subject was again told to relax and look straight ahead.

For the cardiovascular measures, the subject was seated in an acoustically isolated testing room (193 cm deep, 183 cm wide) and the electrodes and blood pressure cuff were attached. In order to induce a variety of autonomic demands, cardiovascular variables were recorded during each of seven four-minute epochs. During the first, third, fifth, and seventh epochs, the subject sat still and was told to relax. During the second and fourth epochs the subject engaged in either a cold face stress task or a reaction time / shock-avoidance task (the order of these tasks was counterbalanced). During the sixth epoch, the subject performed the two tasks simultaneously.

During the cold face stress the subject sat still while an experimenter held a plastic bag of cold water (8–10°C) against the subject's forehead. This task has been shown to induce parasympathetic activation of the cardiovascular system by mimicking the human dive reflex (Brick, 1966; Kawakami et al., 1967; Khurana et al., 1980; Thayer et al., 1991; Thayer & Kohler, 1993).

The shock avoidance/reaction time task was designed to induce sympathetic activation (Sherwood et al., 1986). Prior to this task the subject determined the maximum intensity of the electrical shock that he or she was willing to experience. As the experimenter gradually increased the intensity (starting from the lowest setting) and delivered brief (0.5 s) shocks, the subject instructed the experimenter when an appropriate shock intensity had been reached and the shock level was then fixed at that level. During the task, the subject fixated a video monitor and held a response button. He or she was instructed to press the response button as quickly as possible after the simultaneous presentation of a beep and the word "GO" on the monitor. The subject was also told that a shock would be administered (at the predetermined intensity) if the reaction time was longer than a randomly fluctuating criterion value. Following each trial, the reaction time was briefly displayed on the monitor. In reality, the shocks were not linked with the reaction times. Instead, the subject received only one shock after the first trial in the third minute of the task.

During all recording epochs the subject controlled his or her breathing at a rate of 15 breaths per minute (timed with a metronome). Controlled respiration facilitates the assessment of vagally mediated heart rate variations (Grossman et al., 1991), standardizes high-frequency variations in heart rate, and facilitates the distinction between low- and high-frequency heart rate variations.

Quantification of cardiovascular data. During ECG sampling, software recognized the R-spikes and computed and stored the temporal duration between adjacent R-spikes (i.e., the sequence of interbeat intervals; IBIs) for later analysis. Following data acquisition, a preprocessing algorithm replaced any artifactual intervals with estimates based on interpolation from the two proceeding and two succeeding valid intervals. Variables derived from this sequence of IBIs included the mean IBI, the variance around this mean, and the mean successive difference (MSD; the average difference between adjacent IBIs). To analyze the autonomic influences on cardiac activity, an autoregressive spectral decomposition of the sequence of IBIs was performed off-line using the continuous spectral estimation technique described by Colombo et al., (1989). This process estimates the spectral power as a function of frequency, and determines the locus of the fundamental frequency components. Such an analysis typically yields frequency components that represent IBI variations at a low frequency (LF; centered around 0.039–0.15 Hz) and a high frequency (HF; centered around 0.20–0.35 Hz). LF and HF power values, which primarily index sympathetic and parasympathetic control of heart rate, respectively, are initially specified in power spectral density units ($msec^2/Hz$). To obtain indices that are independent of the total variation in IBIs, the raw LF and HF power values were transformed into a percentage of the total spectral power (less any power at frequencies lower than LF frequencies). The ratio of LF power / HF power provides an index of the relative strength of sympathetic and parasympathetic forces (with larger values indicating relative sympathetic dominance).

Data Reduction

Because this experiment was concerned with the individual differences (trait characteristics) in the subjects' oculomotor and cardiovascular traits, all electrocardiographic variables were computed individually for each epoch and were then averaged across the seven epochs. Although these averages provide valid estimates of cardiovascular traits, it is important to remember that these epochs were by intention quite different and that the averages do not reflect autonomic functioning in any one situation. This approach is in line with recommendations that trait characteristics should be estimated through the averaging of repeated measurements that were made over different situations (Epstein, 1979; Epstein & O'Brien, 1985; Hundleby et al., 1965; Nesselroade, 1990). To estimate subjects' oculomotor traits, the five measures of dark focus were averaged, as were the three measures of dark vergence.

Results and Discussion

In determining what predictor variables to include in multiple regression analyses, it is desirable to be consistent with existing theory and data. The model of heart rate control provided by Levy and Zieske (1969) provided guidance for the present analyses. This model includes an index of sympathetic activity, an index of vagal activity, the product of the sympathetic and vagal indices (representing the non-linear component of the interaction between these branches), and the squares of the sympathetic and vagal indices. Consistent with this model, LF, HF, the product of LF and HF, and their squares were used to predict dark vergence and dark focus.

In the analysis to predict dark focus, one of the five predictors in the regression model (LF^2) was forced out of the analysis due to multicollinearity. The resulting regression model could not successfully predict dark focus [$F(4,5) < 1.0$]. In interpreting this negative finding, it is important to realize that the statistical power of this analysis is weak due to the small number of subjects (accommodative data are available for only 10 subjects). The model did, however, explain 40% of the variability in dark focus ($R^2=.404$).

The attempt to predict dark vergence was more successful [$F(5,6)=4.98, p=.038$] and accounted for 80% of the variability in dark vergence ($R^2=.806$). Figure 1 gives the regression model and shows the close relationship of each subject's dark vergence to the corresponding dark vergence value that was predicted by the regression model. This result indicates that the parameters that quantify the autonomic control of heart rate are also related to the tonic level of the vergence system. One possible explanation of this relation is that the pattern of autonomic activation that reaches the cardiovascular and vergence systems is linked.

Experiment 2

To explore further the between-subjects relationship between cardiovascular and oculomotor behavior, measures of each were obtained from subjects who experience two different forms of anxiety—blood phobia and panic. In addition to grossly different symptoms (e.g., phasic bradycardia and syncope accompanying blood phobia; phasic tachycardia accompanying panic attacks), these groups have been shown to exhibit distinctive patterns of autonomic cardiac control. Friedman et al. (1993) ascertained that panickers exhibit relative sympathetic dominance of cardiac control in comparison to the relative parasym-

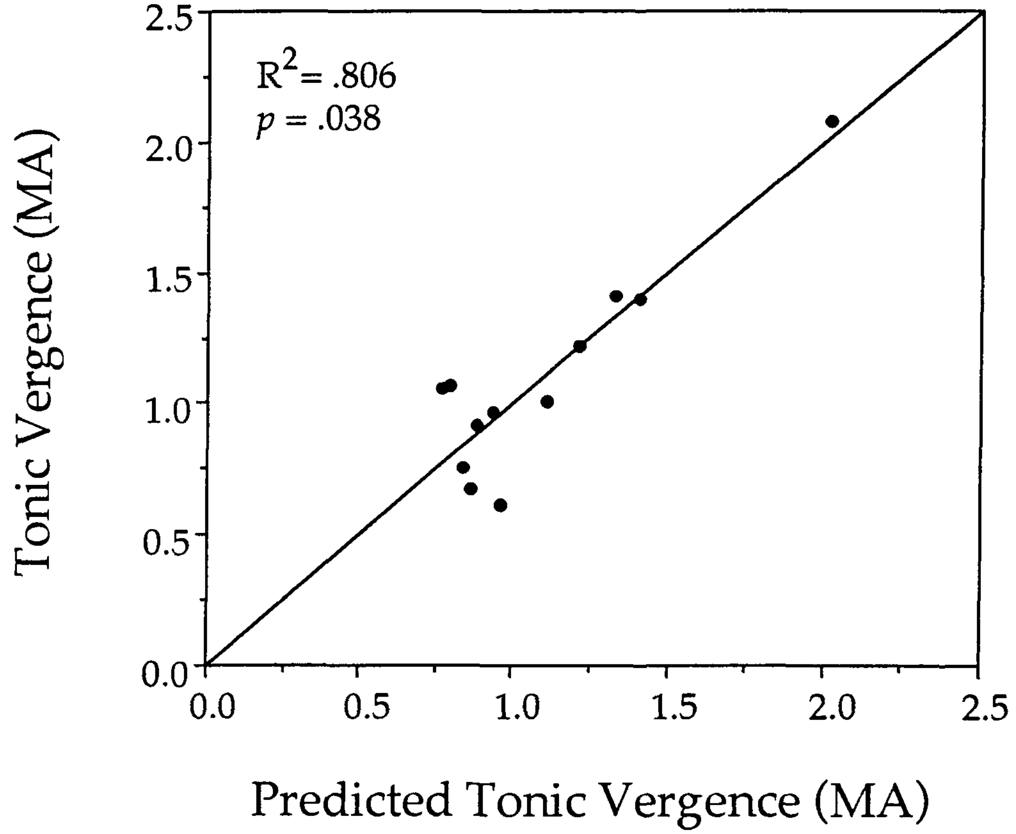

FIG. 1. Results of the regression model that successfully used autonomic indices of cardiac control to predict TV. The actual regression model was TV = .29 + (6.0e-4 * LF) + (2.7e-4 * HF) + (–3.9e-7 * LF*HF) + (5.0e-7 * LF^2) + (1.08e-8 * HF^2).

pathetic dominance shown by blood phobics. Using the same subjects that were used in the Friedman, et al. study, the present experiment used correlational and pattern classification analyses to determine whether these cardiovascularly distinct groups also exhibited distinctive oculomotor characteristics.

Method

Subjects. To establish the two subject groups, approximately 700 introductory psychology students responded to two questionnaires. Each questionnaire was designed to use the DSM-III-R criteria to identify individuals who experience either blood phobia or panic attacks. The panic questionnaire was based on a survey previously used to recruit a panic disorder analog sample (Michelson, et al., 1990) and included a description of panic attacks and resulted in a score that was based on the frequency and self-rated severity of attacks. For those individuals that reported having fainted at least once in response to the sight of blood, the blood phobia questionnaire summed the intensity scores of a number of somatic symptoms of blood phobia.

From the pool of respondents, the individuals who scored the highest on these questionnaires were recruited to participate in the experiment (see Friedman et al., 1993 for details concerning questionnaires and subject selection). These procedures resulted in 11 subjects in the panic attack group (mean age of 19.1 years; standard deviation of 1.2 years) and nine in the blood phobia group (mean age of 19.3 years; standard deviation of 1.2 years). All 20 subjects were female, reported no health problems, and had agreed to abstain from caffeine, nicotine, and alcohol for at least 12 hours prior to the experiment. None of the subjects wore spectacles, and all exhibited a far binocular acuity of 20/30 or better and a lateral heterophoria of not more than 4.0 prism diopters from othophoria (Titmus Vision Tester). Subjects provided their written consent prior to the experiment and were paid for their participation. Due to equipment difficulties, accommodative data are not available for three subjects and cardiovascular data are not available for another.

Apparatus and Procedures. All equipment and procedures were identical to those described for Experiment 1. All electrocardiographic variables were again averaged across the seven experimental epochs.

Results and Discussion

Consistent with the findings of Friedman et al. (1993), the average heart rate of the panic attack group was nearly 10% higher than that of the blood phobia group [$t(12) = 2.07$; 1-tailed $p = .03$]. There were no between-group differences for either dark focus [$t(13) = 0.27$; $p > .10$] or dark vergence [$t(14) = 0.35$; $p > .10$]. Thus it appears that the oculomotor system is not influenced by the same static factors that mediate heart rate. What is more interesting, however, is the potential covariation between the oculomotor and cardiovascular systems. Consistent with the finding that dark vergence values were lower (more distant) during relaxation (Miller & Takahama, 1988), Figure 2 shows that heart rate was positively related to dark vergence [$r = .41$; $t(17) = 1.84$; 1-tailed $p = .04$]. Subjects with slower heart rates tended to have lower (more distant) dark vergence values. Dark focus and heart rate were not significantly related [$r = .40$; $t(14) = 1.64$; 2-tailed $p > .10$].

There were no significant correlations among dark focus, dark vergence, and the parameters that were derived (and then averaged) from the spectral decomposition to index independently sympathetic and parasympathetic cardiac control. Since it is possible that the oculomotor variables are influenced by both autonomic branches, however, a more sophisticated analysis is needed to determine if there are *patterns* that describe the interactions between these variables.[2] Toward this end, multivariate pattern classification analyses (Huberty, 1984; Johnson & Wichern, 1988) determined the degree to which the two groups of subjects could be differentiated by the information contained in the oculomotor and cardiovascular data sets. Due to the expected nonlinearity in these systems, non-linear classification was achieved by using higher order terms of the predictor variables (Duda & Hart, 1973; Pao, 1989).

In determining what predictor variables to include in these analyses, the model of heart rate control provided by Levy and Zieske (1969) again provided guidance, and the first pattern classification analysis used as predictors heart rate, LF, HF, the product of LF and HF, and their squares. The results of this analysis are summarized in Table 1 and indicate that the cardiovascular variables are sufficient to distinguish between the two panic and blood phobic groups. Overall, only two of the 19 subjects were misclassified. This 89.5% correct classification rate is statistically significant [$z = 3.33$; $p < .0001$], and represents a 78.4% increase from that expected by chance (Thayer et al., 1992). While this provides further support for a physiological (cardiovascular) distinction between the two groups,

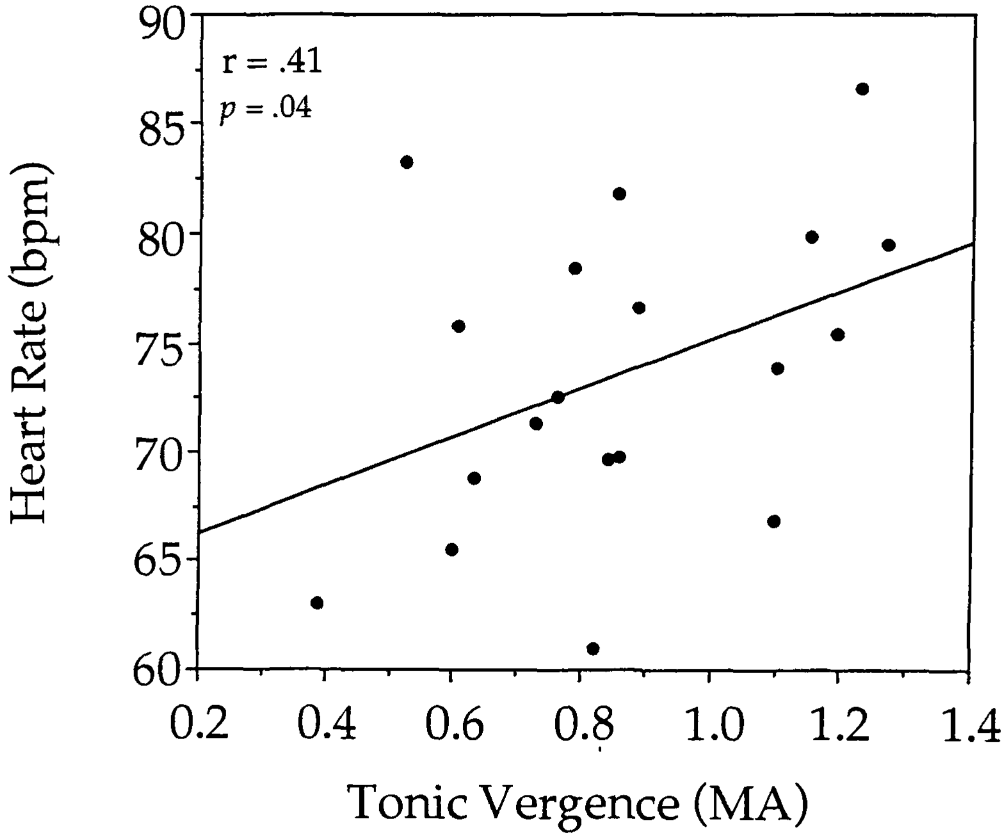

FIG. 2. The relationship between mean heart rate and TV indicates that those subjects with a faster heart rate tended to also have a higher TV value (i.e., a nearer TV posture).

what is more relevant is whether oculomotor variables are sufficient to distinguish between these same groups.

In determining which variables to use as oculomotor predictors, no theory or data were available to provide guidance. In such situations, the inclusion of higher order terms is recommended ("selective enhancement" of the predictor variables; Pao, 1989). Because the addition of higher order terms leads to a geometric increase in the number of input variables, "pruning" of the input vectors is necessary to remove terms that are highly collinear. This process led to the use of dark focus, dark vergence, and their cubes as predictors. The results of the pattern classification analyses are summarized in Table 2 and indicate that the panic and blood phobic groups are indeed separable based on these predictors. Overall, 13 of the 17 subjects (76.5%) were classified into their correct group. This correct classification rate is significant [z = 2.11; p = .017], and represents a 52.1% increase from that expected by chance alone. Thus these two groups, who have been shown to be cardiovascularly distinct, possess distinctive patterns of oculomotor behavior as well.

Two findings from this experiment provide evidence for a behavioral link between the oculomotor and cardiovascular systems—the correlation between heart rate and dark

	TRUEGROUP	
	Panic Attack	Blood Phobia
PREDICTEDGROUP		
Panic Attack	10	1
Blood Phobia	1	7

n correct	10	7
total *n*	11	8
proportion correct	.909	.875

total *n* = 19 total *n* correct = 17 total proportion correct = .895

TABLE 1. Results of pattern classification analysis that sought to predict the group to which each subject belonged based on the cardiovascular variables—heart rate, LF, HF, LF*HF, LF^2, and HF^2.

vergence, and the separability of the two subject groups based on both oculomotor or cardiovascular variables.

Experiment 3

Capitalizing on a methodological advance that allowed the simultaneous assessment of cardiovascular and oculomotor activity, Experiment 3 probed whether oculomotor-cardiovascular covariation exists on a within-subjects basis. Each subject participated in four experimental sessions during which he or she experienced a variety of conditions.

Method

Subjects. Three undergraduate students volunteered. Subject 1 was a 20-year-old male with a height of 190.5 cm (75") and a weight of 90 kg (198 pounds). He wore no optical correction, and achieved 20/20 far acuity with each eye. Subject 2 was a 21-year-old female 167.6 cm (66") tall and weighing 62 kg (137 pounds). With her contact lenses she achieved 20/25 far acuity with each eye. Subject 3 was a 21-year-old female 162.6 cm (64") tall and weighing 51 kg (112 pounds). With her contact lenses she achieved 20/20 far acuity with each eye. All subjects were nonsmokers and were asked to abstain from caffeine and alcohol during the 12 hours prior to each experimental session, and all reported having complied with this request. None reported taking any medication at any time throughout the duration of their participation, and none reported any health or visual problems.

Apparatus. Oculomotor and cardiovascular variables were assessed using the same equipment as was described previously.

	TRUE GROUP	
	Panic Attack	Blood Phobia
PREDICTED GROUP		
Panic Attack	8	3
Blood Phobia	1	5

n correct	8	5
total *n*	9	8
proportion correct	.889	.625

total $n = 17$ total n correct = 13 total proportion correct = .765

TABLE 2. Results of pattern classification analysis that sought to predict the group to which each subject belonged based on the oculomotor variables—TA, TV, TA^3, and TV^3.

Procedure. Prior to the first experimental session, each subject came to the lab for an initial screening and practice session. During this screening session, the subject was given verbal and written explanation of the procedures, after which the subject gave his or her informed consent. Distance acuity, interpupillary distance, and the subject's accommodative response to a high-contrast acuity chart at 6 m were measured. As was done previously, the value of this accommodative response was subtracted from that subject's dark focus values. The subject was also familiarized with the procedures for dark focus and dark vergence measurement, and at least three practice measurements of dark vergence were made.

Each subject participated in four separate experimental sessions, each lasting approximately 90 minutes. The four sessions were identical with the exception of the counterbalanced ordering of the two epochs that were designed to induce sympathetic and parasympathetic activation (epochs 2 and 4). Upon arriving for an experimental session, the subject was seated in the acoustically isolated testing room and was reminded of the procedures while the electrodes and blood pressure cuff were attached. Dark vergence, dark focus, ECG, blood pressure, and two measures of dark vergence and 20–40 measures of dark focus were recorded during each four-minute epoch. These epochs were similar to those described previously. However, because all seven had to be conducted in complete darkness the reaction time / shock-avoidance task was replaced with a grip strength / shock-avoidance task.

The grip strength / shock-avoidance task, like the reaction time / shock-avoidance task, was intended to induce sympathetic activation. Other studies have documented the effectiveness of both shock-avoidance and hand grip tasks at inducing sympathetic reactions (Sherwood et al., 1986; Miller, 1993; Pollak & Obrist, 1988). Prior to performing this task, the subject determined the intensity of the shock (using the same procedure as described previously) and the maximum grip force (determined by having the subject briefly squeeze a hand dynamometer as forcefully as possible with the left hand). During the task, the subject squeezed the dynamometer and, whenever the grip force dropped below the target grip force, heard an experimenter say either "Warning" or "Shock." The experimenter delivered a shock concurrently with the latter warning. Although the target grip force was initially 25% of the subject's maximum grip strength, the experimenter actually employed a sliding target grip force to ensure that the subject received 3–5 shocks (and approximately twice as many warnings) throughout the four-minute task.

During all of the recording epochs the subject controlled his or her breathing at a rate of 15 breaths per minute (timed with a metronome). Due to equipment difficulties, parameters derived from the autoregression analysis are not available for one condition in Subject 1's first session, for one condition in Subject 3's second session, and for one condition in Subject 3's fourth session.

Results and Discussion

To analyze the effects of the epochs on the oculomotor and cardiovascular variables a Simes multiple comparison procedure (Wilcox, 1987a; 1987b) tested the significance of their differences across the Ice, Grip, and Combination conditions.[3] Because the Ice and Grip conditions were designed to induce sympathetic and parasympathetic activation, respectively, directional hypotheses had been made concerning the difference between the Ice and Grip conditions and tests comparing the cardiovascular effects of these two conditions were 1-tailed. Table 3 presents the multiple comparison results which were, in the case of the cardiovascular variables, manipulation checks. The magnitude of the effects were described by the effect size (Friedman, 1968) and can be visualized in Figure 3. Data from the baseline and three recovery conditions were not analyzed for condition effects.

In general, the manipulations had the expected effect on the cardiovascular variables. The Ice condition was associated with significantly longer IBIs, greater IBI variance, and greater mean successive differences than the Grip condition. These effects suggest that relative to the Grip condition, the Ice condition was associated with parasympathetic dominance of the heart. This notion was supported by the fact that the LF/HF ratios and systolic and diastolic blood pressure were significantly lower in the Ice condition than in the Grip condition and by the nonsignificant tendency for there to be more HF power and less LF power in the Ice condition than in the Grip condition. Results from the Combination condition, although mixed, suggest that the autonomic activation tended to be dominated by sympathetic activity—although the differences between the Combination and Grip conditions were not significant, the Combination condition was associated with the even shorter IBIs, smaller mean successive differences, and higher systolic and diastolic blood pressures, but smaller LF/HF ratios.

Table 3 and Figure 3 also present the variations in dark vergence and dark focus. Dark vergence was 0.15 MA nearer in the Grip condition than in the Ice condition. Although this effect is not significant after the Simes correction, the difference is similar in both magnitude and direction to that reported by Miller and Takahama (1988), who measured dark vergence to be approximately 0.15 MA farther during deep relaxation condition than in their other conditions. Dark focus was significantly nearer in the Grip condition than in the Ice condition (0.23 D). The direction of this effect is inconsistent with previous reports that dark focus is nearer during relaxation than during such demanding tasks as mental activity, cold pressor, or following viewing of aversive slides (e.g., Miller & Takahama,

	Grip – Ice (1-tailed tests)	Combo – Ice (2-tailed tests)	Combo – Grip (2-tailed tests)
Dark Vergence (MA)	Difference = 0.153 $t(11) = 1.80; p = .049$ $r_m = .48$	Difference = 0.023 $t(11) = 0.67$; ns $r_m = .20$	Difference = –0.129 $t\ (11) = 1.59$; ns $r_m = .43$
Dark Focus (D)	Difference = 0.226 $t(11) = 3.15$; 2-tailed $p = .009$* $r_m = .69$	Difference = 0.189 $t(11) = 2.10$; ns $r_m = .53$	Difference = –0.034 $t(11) = 0.49$; ns $r_m = .15$
Inter-beat Interval (msec)	Difference = –87.6 $t(11)=5.62;p= .0001$* $r_m = .86$	Difference = –124.8 $t(11)=5.01;p= .0004$* $r_m = .83$	Difference = –37.2 $t(11) = 2.03$; ns $r_m = .52$
IBI Variance ($msec^2$)	Difference = –1413 $t(11) = 2.54; p = .014$* $r_m = .61$	Difference = –684 $t(11) = 0.84$; ns $r_m = .25$	Difference = 2571 $t(11) = 2.78; p = .018$ $r_m = .64$
Mean Successive Differences (msec)	Difference = –13.83 $t(11) = 3.12; p=.005$* $r_m = .69$	Difference = –18.92 $t(11) = 3.14; p=.009$* $r_m = .69$	Difference = 5.08 $t(11) = 1.94$; ns $r_m = .50$
LF Power (%)	Difference = 5.28 $t(11) = 1.19$; ns $r_m = .34$	Difference = 1.43 $t(11) = 0.33$; ns $r_m = .10$	Difference = –3.86 $t(11) = 1.18$; ns $r_m = .34$
HF Power (%)	Difference = –6.80 $t(11) = 2.03; p = .034$ $r_m = .52$	Difference = –3.30 $t(11) = 0.69$; ns $r_m = .20$	Difference = 3.50 $t(11) = 1.08$; ns $r_m = .31$
LF/HF Ratio	Difference = 0.517 $t(9) = 2.57; p = .015$* $r_m = .65$	Difference = 0.159 $t(9) = 0.84$; ns $r_m = .27$	Difference = 0.341 $t(9) = 1.98; p = .08$ $r_m = .55$
Systolic Blood Pressure (mm Hg)	Difference = 12.83 $t(11) = 4.30; p<.001$* $r_m = .79$	Difference = 15.17 $t(11) = 5.52; p< .001$* $r_m = .86$	Difference = 2.33 $t(11) = 0.98$; ns $r_m = .28$
Diastolic Blood Pressure (mm Hg)	Difference = 6.17 $t(11) = 2.74; p=.001$* $r_m = .64$	Difference = 10.17 $t(11) = 3.12; p=.001$* $r_m = .69$	Difference = 4.00 $t(11) = 1.48$; ns $r_m = .41$

TABLE 3. Statistical comparisons among the three "active" conditions for the oculomotor and cardiovascular variables. An asterisk indicates that the difference remains significant with a Simes correction (family-wise error probability = .05). With the exception of the dark focus comparison, all significance tests between the Grip and Ice conditions were one-tailed.

1987; 1988). But the finding is consistent with reports of inward accommodative shifts in subjects who were anxious, angry, or insulted (Leibowitz, 1976; Miller, 1978; Miller & LeBeau, 1982; Westheimer, 1957) and with the recent finding that the dark focus is nearer after running 400 m than before running (Ritter & Huhn-Beck, 1993). Given that the Grip and Ice manipulations effectively induced autonomic / cardiovascular shifts in the expected direction, the present data indicate that dark focus was nearer during sympathetic dominance of the cardiovascular system than during parasympathetic dominance.

To examine further the relationship between the cardiovascular and oculomotor sys-

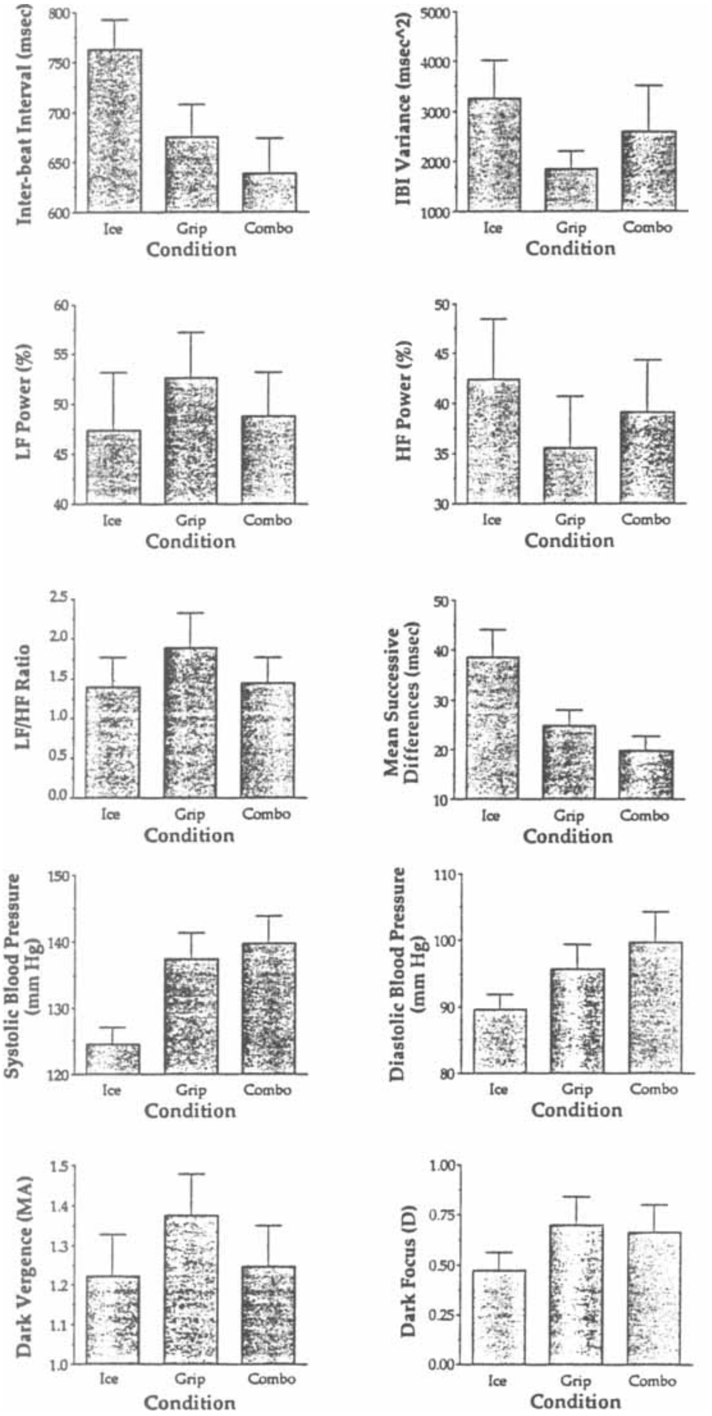

FIG. 3. Mean values (+1 standard error of the mean) of cardiovascular and oculomotor parameters in the three "active" conditions.

tems, a hierarchical regression analysis was employed to determine if a theoretically relevant group of cardiovascular parameters could predict the oculomotor resting states. Again, the predictors included the sympathetic (LF) and parasympathetic (HF) cardiac influences, the interaction between these two forces (LF*HF), and their second order influences (LF^2 and HF^2). Taking advantage of the fact that cardiovascular and oculomotor indices were assessed concurrently, data were used from all 81 available cases (3 subjects × 4 sessions × 7 conditions – 3 cases with missing data). Because it was necessary to determine if the cardiovascular parameters could account for a significant portion of variability in addition to that already accounted for by the individual differences, the mean of the predicted variable (either dark vergence or dark focus) for each subject was entered into the regression model in the first step, and the five cardiovascular parameters were entered in the second step. This procedure allows for the statistical determination of whether the cardiovascular variables as a group add a significant amount of predictive power to that already provided by the knowledge of the variations in the oculomotor variables that occurred among subjects (Neter et al., 1985, p. 290). Table 4 summarizes the results of these analyses. Beyond the variability that was due to individual differences and variations among sessions, the cardiovascular parameters accounted for no additional dark vergence variability but did account for an additional 8.7% of the variability in dark focus. This increment in R^2 was significant ($F[5,74] = 2.87$; $p < .05$; $r_m = .40$).

While these regression analyses indicate that a theoretically relevant set of cardiovascular indices could predict dark focus but not dark vergence, similar analyses in Experiment 1 indicated that the same set of parameters could predict dark vergence but not dark focus. Although the reasons for this discrepancy are not clear, the distinction between within-subjects and between-subjects variations appears to be an important one. Taken together, results from Experiments 1 and 3 indicate that between-subjects variations in dark vergence and within-subjects variations in dark focus can be partially accounted for by similar variations in cardiovascular parameters.

Univariate correlations between oculomotor tone and mean IBI were also examined. The correlation between dark vergence and IBI was –.40 ($F[1,82] = 16.07$; $p < .001$). On average, IBIs were shorter during trials in which dark vergence was near. The magnitude and direction of this relationship are similar to that found in Experiment 2. The correlation in the present Experiment, however, combines within- and between-subjects variability. To determine the degree to which this relationship exists within individuals, a hierarchical regression analysis again entered each individual's mean dark vergence in the first step and the IBI in the second step. This analysis indicated that once the between-subjects variations in dark vergence were removed, IBIs could no longer predict dark vergence (increment in $R^2 = .003$). Thus it appears that IBIs predict between-subjects variability in dark vergence but not within-subjects variability. IBIs were not related to dark focus ($r = -.07$; $F[1,82] = 0.40$; $p > .10$).

To summarize, the manipulations resulted in systematic variations in both the cardiovascular and oculomotor systems. Similar to previous findings by Miller and Takahama (1988), dark vergence was nearer during sympathetic dominance. Dark focus was also nearer during sympathetic dominance, a result that seems inconsistent with dual-innervation theory but is consistent with a number of investigations on accommodation during emotional and physical activation. Parameters that quantify the autonomic activation of the heart can be used to predict dark focus, but not dark vergence, on a within-subject basis. Finally, due mostly to between-subjects differences, dark vergence was negatively correlated with IBIs.

Predictor Variables	*R^2 for Dark Vergence*	*R^2 for Dark Focus*
Subject mean	.733	.555
Subject mean, LF, HF, LF*HF, LF^2, HF^2	.733	.642
Increment	.000	.087

TABLE 4. Results of hierarchical regression analysis to determine if cardiovascular model can predict dark vergence and dark focus. Values given represent the proportion of variance in the predicted variable accounted for by the specified group of predictor variable.

GENERAL DISCUSSION

These experiments demonstrate behavioral covariation between the oculomotor and cardiovascular systems. Hierarchical regression analyses in Experiment 1 indicated that variables that quantify the autonomic control of heart rate can predict individual differences in dark vergence (but not dark focus). Two results from Experiment 2 provided further evidence for intersubject behavioral covariation—a positive correlation between heart rate and dark vergence and the finding that two cardiovascularly distinct groups of anxious subjects have distinctive oculomotor resting states. By assessing cardiovascular and oculomotor activity simultaneously, Experiment 3 addressed whether the oculomotor-cardiovascular covariation exists on a within-subject basis. Relative to the Grip condition, the Ice condition was characterized by a pattern of cardiovascular responses indicating a relative parasympathetic dominance of the heart and by outward shifts of dark vergence (0.15 MA) and dark focus (0.23 D). While demonstrating behavioral covariation between the oculomotor and cardiovascular systems, these experiments also provide suggestive evidence that autonomic mechanisms may underlie the link between the two systems.

The sizable literature describing the autonomic control of accommodation has yielded inconsistent conclusions. While much of the evidence indicates that parasympathetic activation mediates inward accommodative shifts and that sympathetic activation slowly shifts accommodation outward, some reports indicate that dark focus shifts inward during emotional and physical "arousal." The results from Experiment 3 are consistent with this latter group of studies—dark focus was 0.23 D nearer during sympathetic dominance of the cardiovascular system. This result is intriguing, as it seems to be inconsistent with dual-innervation theory. Given the present data and the inconsistencies in the literature regarding autonomically induced shifts in dark focus, the interactions between autonomic activity and dark focus appear to be considerably more complex than the simple balance between two opposing linear forces that dual-innervation theory suggests. The inward shift associated with sympathetic dominance of the cardiovascular system may have implications for visual performance in demanding and stressful conditions, and under strong real-world demands, the oculomotor effects might be even larger.

Results from each of the three experiments support a behavioral link between dark vergence and cardiovascular activity: a theoretically relevant set of cardiovascular parameters predicted individual differences in dark vergence, a positive correlation between individual differences in dark vergence and heart rate was found, and dark vergence and cardiovascular parameters were found to covary on a within-subjects basis. Although the traditional dual-innervation theory does not address vergence control, this evidence, together with the behavioral evidence presented by Miller and Takahama (1988) raises the possibility of an autonomic input to the vergence system. Consistent with this are: 1) neuroanatomical reports indicating afferent nerve fibers that carry proprioceptive information from the extraocular muscles to the ophthalmic branch of the trigeminal nerve, which is a vagal afferent (Porter, 1986; Wilson-Pauwels et al., 1988); 2) evidence that both injections of epinephrine and electrical stimulation of the superior cervical ganglion give rise to dose- and voltage-dependent tonic contractions of extraocular muscles in intact cats (Eakins & Katz, 1967; 1971); and 3) the existence of the vagally mediated oculocardiac reflex (Alexander, 1975; Mallinson & Coombes, 1960). Further research will be necessary to explain the neurophysiological mechanisms that may be responsible for a link between vergence and the ANS. One way to address this question in humans would be to determine whether the behavioral covariation is robust to reduced ANS functioning. Thus it might be informative to repeat the type of manipulations used in the present experiments with and without blockage of autonomic pathways. If autonomic mechanisms are responsible for the eye-heart link, then autonomic blockades (either pharmacologically induced or occurring naturally as a result of functional autonomic disorders) would attenuate the covariation. The examination of the response of other visual variables that may covary with cardiovascular alterations would also be fruitful. Recent findings indicate that the spectral decomposition of closed-loop variations in accommodation can be useful for probing autonomic mechanisms (e.g., Winn, Gilmartin, & Strang, 1993).

In addition to uncovering the mechanisms responsible for the eye-heart link, future studies may explicate circumstances in which the link has considerable practical importance. Given that the oculomotor resting states vary with cardiovascular demands, it is possible that these variations will affect visual performance in demanding situations. For example, tasks involving prolonged exposure to near visual distances have been shown to result in both inward shifts in dark focus and dark vergence and in a reduction in the ability to see distant targets (e.g., Owens & Wolf-Kelly, 1987; Tyrrell & Leibowitz, 1990). The results from the Grip condition in Experiment 3 indicated that tasks that lead to sympathetic dominance of the cardiovascular system can also lead to inward shifts in the oculomotor resting states. It remains to be tested whether these shifts also have performance implications.

The present results do not specify a unidirectional relationship between cardiovascular and oculomotor variations. In a recent study, cardiovascular activity was monitored from 17 young adults who spent 20 minutes reading text from a video display terminal at a near distance of 20 cm (Tyrrell & Thayer, 1994). Nine of the 17 subjects exhibited inward shifts in dark vergence, and seven subjects showed inward shifts in dark focus. Preplanned linear contrasts indicated that the subjects who experienced these oculomotor shifts also experienced significant linear decreases in interbeat intervals ($p < .01$) and in HF power ($p < .01$), as well as nonsignificant increases in LF power and in the LF/HF ratio ($p > .05$). Subjects who did not experience oculomotor shifts exhibited fewer and smaller cardiovascular changes. These results indicate that an acute vagal withdrawal accompanies the oculomotor shifts that can be induced by near visual work. Although the idea has not yet been tested, it is possible that this vagal withdrawal is related to the link that has been established between the magnitude of near-work induced shifts in dark vergence and the severity of subjective symptoms of visual discomfort associated with near visual work (Owens & Wolf-Kelly, 1987; Jaschinski-Kruza, 1991; Tyrrell; & Leibowitz, 1990).

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Notes

1. Two findings by Miller and Takahama are consistent with the possibility that the ANS controls vergence directly. First, the shifts in dark vergence and dark focus were in opposite directions, with dark vergence shifting outward during relaxation and dark focus shifting inward during conditions intended to invoke a parasympathetic response. Second, the correlations between arousal ratings and dark focus and dark vergence were also in opposite directions. Although arousal ratings and dark vergence were correlated at +.76, the correlation between dark focus and the same arousal ratings was -.67.

2. This is consistent with a statement made by Gawron in 1983. In a review of relationships among accommodation, personality, and autonomic balance, Gawron asserted that the relationships between these constructs "may elude conventional statistics based on linear assumptions" (p. 637).

3. This procedure dictates that the q means be compared by using standard t tests, ordering the resulting p values in ascending order, then sequentially rejecting the null hypothesis of any comparison in which the p value is smaller than the critical value given by $j\alpha/q$, where $j = 1$, k, and $\alpha = .05$. Like other multiple comparison techniques, this procedure does not require a significant F test as a pre-requisite. Three outlying values of the LF/HF ration (all>7) were excluded.

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