The influence of cardiac phase on reaction time depending on heart period length and on stimulus and response laterality

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The aim of this study was twofold: (1) to reinvestigate the question of cardiac cycle time effect on sensorimotor performance, and (2) to examine the dependence of this effect on stimulus and response laterality. Thirty-eight right-handed subjects performed a simple visual reaction time task, where stimuli were presented randomly to the right or to the left of the fixation point, or centrally. Half of the responses were given by the right hand, and the other half by the left hand. The stimuli occurred at either 150- or 600-msec delays from the R wave of the electrocardiogram, that is, during the systolic or diastolic part of the cardiac cycle, respectively. For right stimuli and right-hand responses, the reaction time was marginally longer for systolic than for diastolic stimuli. No such effect emerged for central and left-hand responding. This result suggested—albeit weakly—that the sensorimotor functions of the left cerebral hemisphere might be influenced to a greater extent by the physiological changes accompanying cardiac activity than those of the right hemisphere. Additionally, it was shown that in females characterized by long heart periods, the reaction time was longer for stimuli presented during systole than for stimuli presented during diastole, but the opposite was true in males with short heart periods. In males, a similar but nonsignificant tendency was found. This result does not contradict the Laceys' (1970) baroreceptor hypothesis. The limitations of this and similar approaches are discussed.

Ample evidence indicates that baroreceptor activation has a profound inhibitory effect on various activities of the central nervous system, including those of the cortex. Stimulation of the baroreceptors was shown to have a synchronizing effect on the electroencephalogram (Bonvallet, Dell, & Hiebel, 1954), to inhibit monosynaptic reflexes (Bonvallet, Dell, & Hugelin, 1954), to decrease the amplitude of optic evoked potentials (Koella, Smythies, Levy, & Czicman, 1960), to suppress sham rage (Bartorelli, Bizzi, Libretti, & Zanchetti, 1960), to inhibit cell activity in the nucleus cuneatus (Gahery & Vigier, 1974) and in the motor cortex (Coleridge, Coleridge, & Rosenthal, 1976), to reduce nictating membrane and sweat gland activity (Horrowitz & Kaufman, 1979), and to reduce the amplitude of slow brain potentials (Rau, Pauli, Brody, Elbert, & Birbaumer, 1993). Some of these neurophysiological findings led Lacey and Lacey (1970) to suggest that baroreceptor activation accompanying cardiac acceleration and baroreceptor deactivation accompanying cardiac deceleration may have behavioral significance by influencing cortical activation. They proposed that cardiac acceleration impairs sensorimotor performance, while the opposite is true for cardiac deceleration.

The Laceys' first results and their so-called baroreceptor hypothesis inspired several studies that investigated whether the timing of stimulus presentation within the cardiac cycle has an impact on the reaction time (RT). It is well known that during systole the baroreceptors of the carotid sinus and of the aortic arch are stimulated by blood pressure elevation, whereas during diastole, the blood pressure decrease results in the deactivation of the baroreceptors. On the basis of this fact, it was reasonable to assume that reaction time should be more prolonged during the systolic phase of the cardiac cycle than during the diastolic phase. Birren, Cardon, and Phillips (1963) were the first to report that in a simple reaction time experiment, responses to auditory stimuli were fastest when stimuli occurred during the P wave of the electrocardiogram (EKG), that is, during diastole.

Similar cardiac cycle time effects on reaction time were found by Callaway and Layne (1964), Saari and Pappas (1976), and Wynn (1980) (for review, see Coles & Strayer, 1985). It must be noted, however, that other researchers have failed to find such an effect (Coles, Pellegrini, & Wilson, 1982; Jennings & Wood, 1977; Thompson & Botwinick, 1970). Toon, Bergel, and Johnston (1984) artificially manipulated baroreceptor activity by inflating and deflating a neck collar, but these manipulations did not produce significant changes in reaction time.

The results of other studies trying to relate stimulus detection performance to cardiac cycle time are also contradictory. Whereas some of them report a cardiac cycle time effect (Réquin & Brouchon, 1964; Saxon, 1970), others do not (Delfini & Campos, 1972; Elliott & Graf, 1972; Velden & Juris, 1975). Two other studies were supportive of the cardiac cycle time effect on behavior. Oswald (1959) re-
ported that central afterimages fluctuated with pulse rate in 1 subject, and Forsyth (1966) found a cardiac cycle time effect on the number of spontaneous leverpresses.

Another line of evidence indicates that the right cerebral hemisphere plays a greater role in the perception of heartbeats than does the left hemisphere. Both habitual and temporary right hemispheric activation has repeatedly been shown to improve heartbeat perception accuracy as compared to left hemispheric activation (Hantas, Katkin, & Reed, 1984; Montgomery & Jones, 1984; Weisz, Balázs, Láng, & Ádám, 1990). Several heartbeat evoked potential studies (for review, see Jones, 1994) also supported the conclusion that both within- and between-subjects differences in heartbeat perception are reflected primarily in the right hemisphere (Katkin, Cestaro, & Weitkunat, 1991; Montoya, Schandry, & Müller, 1993). On the basis of these results, it has been suggested that the connection between cardiovascular afference and the right hemisphere might be stronger than the connection between cardiovascular input and the left hemisphere (Katkin, 1985; Katkin et al., 1991).

Although various receptors are thought to be involved in the development of heartbeat sensation, baroreceptors are supposed to be among the most important (Montoya et al., 1993, but see Jones, Jones, Rouse, Scott, & Caldwell, 1987). Thus, it seemed logical to assume that right hemispheric functions depend to a greater degree on baroreceptor influences than do functions of the left hemisphere. The results of Walker and Sandman (1982) provide the most direct evidence for this assumption. They reported that visual evoked potentials recorded from the right hemisphere at systolic and diastolic phases of the cardiac cycle differed significantly, whereas those recorded from the left did not. In the right hemisphere the P1 component of the evoked potentials was larger at diastolic pressure (Walker & Sandman, 1982, Experiment 1); this finding was in agreement with the Lacey's (1970) hypothesis. However, when investigating the dependence of spontaneous electrocortical activity on carotid pressure changes within the cardiac cycle, Walker and Walker (1983) were able to demonstrate slower EEG activity during systolic compared to diastolic pressures, but no difference between the hemispheres emerged.

Lateralized presentation of visual stimuli in a reaction time experiment, with stimuli presented during different cardiac phases, makes it possible to investigate the effect baroreceptors exert on the two hemispheres on a behavioral level. It is well known that visual stimuli applied in the right visual hemifield arrive first to the left hemisphere, whereas stimuli presented to the left arrive first to the right hemisphere. Similarly, fine finger movements are controlled exclusively by the contralateral hemisphere (Brinkman & Kuypers, 1973). Thus, a greater sensitivity of the right hemisphere to baroreceptor influences might be reflected in a greater difference between reaction times to systolic and diastolic stimuli when using left visual stimuli and/or left-hand responding. One of the aims of the present research was to test whether such a difference between the hemispheres exists.

Another interesting aspect of the Walker and Sandman study (1982, Experiment 2) was that the difference between systolic and diastolic visual evoked potentials was modulated by heart rate. Evoked potentials recorded from the left hemisphere tended to be larger in the systolic than in the diastolic phase during slow heartbeats, and during fast heartbeats the amplitude difference proved to be non-significant. In the right hemisphere the evoked potentials were larger in the diastolic phase during fast heartbeats, but this effect was absent for slow heartbeats. Although the authors did not offer an explanation for this finding and the finding is at odds with the baroreceptor hypothesis, it also seemed worthwhile to examine the effect of cardiac cycle length on reaction time changes in the present research.

In sum, our primary hypothesis was that the difference between the reaction times to stimuli presented during the diastolic and the systolic cardiac phases would differ depending on whether the stimulus arrived first to the left or the right hemisphere, and whether the motoric component of the reaction was controlled by the left or the right hemisphere. We expected that the difference between systolic and diastolic reaction times would be greater for stimuli presented to the left hemifield and for left-hand responses than for right hemifield stimuli and right-hand responses. On the basis of the Lacey's (1970) hypothesis, we also expected that the diastolic RTs would be faster than the systolic RTs. A secondary hypothesis was that the expected difference between systolic and diastolic reaction times would depend on cardiac cycle length, and, possibly, differently so for the two hemispheres.

METHOD

Subjects
Thirty-eight right-handed university students (21 male and 17 female subjects) with no left-handed first-order relatives volunteered for the experiment and were paid a modest fee. They ranged in age from 19 to 29 years ($\bar{x} = 22.0$ years), and all had normal or corrected-to-normal vision.

Apparatus
During the RT task, visual stimuli were delivered by three red light-emitting diodes (LEDs) with 0.5-cm-diameter round tips. They were mounted on the horizontal midline of a black panel, with one of them located at the center of the panel and the other two placed 20 cm to the right and to the left of the central LED. When ignited by a 10 mA, 50-msec square pulse, each LED produced an easily perceived light flash. The warning signal, presented through a loudspeaker positioned just behind the subject's chair, consisted of a 440 Hz, 500-msec tone. A 2000 Hz, 150-msec tone pip constituted the auditory feedback signal. The response device was a freely movable button key, which could be comfortably held in either hand with the thumb placed on the button, and could be activated by a light press.

Physiological recordings were obtained by a Beckman Type R411 Dynograph. EKG was recorded throughout the RT task by standard lead II electrodes, and a cardiostimulator coupler was used to detect R waves of the EKG. Respiration was recorded from a sphygmomanometer cuff placed around the abdomen of the subject. To monitor eye movements during the RT trials, electrooculographic
(EOG) electrodes were attached to the outer canthi of the eyes, one immediately below and the other immediately above eye level. An AC preamplifier (time constant = 1 sec) was used for amplification of the EOG signal.

The control and timing of the signals and the stimuli, as well as the measurement and storage of interbeat intervals (IBIs) and RTs, were effected by an IBM AT computer located in a room adjacent to the experimental chamber. The accuracy of measurements was ±1 msec. Throughout the experiment the subject was monitored through a closed-circuit TV camera.

**Procedure**

All experiments were performed between 9 and 12 a.m.

The RT task was performed in a sound-attenuated, visually homogeneous experimental chamber where the subjects were left alone. The subjects sat in a comfortable chair with their chins placed on an adjustable chinrest. The stimulus panel was located in front of the subjects at a distance of 80 cm, with the LEDs at eye level and the central LED just directly in front of the eyes. The subjects rested their forearms on a table and their responding hand was placed in the midline. Subjects were instructed to maintain their thumb in contact with the button key throughout each experimental block.

Each RT trial began with an auditory warning signal that told the subject to look at the central LED and that fixation had to be maintained until after they had performed the buttonpress. If the subjects were not fixating, or if they blinked within this time span, as judged from the EOG, the trial was rejected. Following the suggestion of Thompson and Botwinick (1970), the duration of the preparatory interval (the time between the presentation of the warning signal and the stimulus) was composed of four separate time segments. The first portion was a fixed interval of 2 sec. The second portion was either 450 msec (in case of systolic stimulus presentation), or it was completely absent (in case of diastolic stimulus presentation). The third portion was a variable interval that extended from the end of the second portion to the appearance of the next R wave. The fourth portion constituted the R wave-to-stimulus interval, which was either 150 msec (systolic stimuli) or 600 msec (diastolic stimuli). This arrangement ensured that there were no consistent differences between the durations of the preparatory intervals preceding the systolic and diastolic stimuli. Also, the variations of the overall preparatory interval were within the limits of one IBI. The average preparatory interval was somewhat shorter for subjects with a fast heart rate than for subjects with a slow heart rate. However, the difference between any 2 subjects did not exceed 10% of the mean of the overall preparatory interval. At the conclusion of the preparatory interval, the stimulus was presented. The subject was to press the button key as fast as possible upon the appearance of the light flash coming from either LED. An auditory feedback signal informed the subject that the computer received the buttonpress signal. Subsequent to the response there was a 2.5-sec intertrial interval during which subjects were allowed to blink and to move their eyes.

The RT task consisted of four blocks of 72 trials. Each of the three LEDS provided the visual stimulus 24 times within each block. The LEDs emitted half of the light flashes during systole and the other half during diastole. The order of central, right, and left stimuli and that of systolic and diastolic stimuli was randomized with the restriction that no runs with more than four stimuli from the same LED and no runs with more than four stimuli in the same cardiac phase were allowed. The blocks were separated by 3-min rest periods. The responding hand was alternating between the blocks—that is, in two blocks the right hand was used for responding, and in the other two blocks the left hand was used. Half of both males and females responded with their right hand in the first block, and the other half with their left hand. Prior to the experiment the subjects were given detailed instructions and a series of 32 practice trials. At the end of the experiment they were informed about the aim of the experiment and their own performance.

**RESULTS**

RTs between 100 and 600 msec were accepted as stimulus related and RTs shorter than 100 msec or longer than 600 msec were automatically discarded. RTs of less than 100 msec were considered anticipatory responses, and RTs of more than 600 msec were regarded as unacceptably long for simple RTs (see, e.g., Tassinari, Biscaldi, Marzi, & Berlucchi, 1989). Also, trials with cardiac cycles (R-R intervals) shorter than the length of the 600 msec delay were excluded from the analyses. The mean and the standard deviation (SD) of the RTs were computed separately for each subject. Individual RTs that exceeded the value of the subject's mean ±3 × SD were also eliminated. The mean number of trials used in the analyses was 253.7.

In this study, only the IBIs during which the stimuli were presented were analyzed. The mean IBI for centrally presented, diastolic stimuli was computed for each subject, and the subjects were divided into long and short heart period groups (with 19 subjects in each group) on the basis of this value. We used only cardiac cycles with diastolic stimulus presentation to discriminate the two heart period groups because neither stimulus presentation nor response completion could have considerable effect on the length of these cardiac cycles (for a review, see van der Molen, Ba-shore, Halliday, & Callaway, 1991). Mean IBI values in case of central, diastolic stimuli were 766 msec (~78.3 bpm) for the short heart period group, and 983 msec (~61.0 bpm) for the long heart period group. The ratio of males and females did not differ between the two heart rate groups ($\chi^2(1) = .14, p = .744$).

Multivariate analyses of variance (MANOVAs) were conducted on the RT means using the approximate $F$ value computed on the basis of the Pillai's statistic, when appropriate. For familywise testing of the simple effects and for pairwise contrasts, the Bonferroni procedure was used, in which the level of significance is divided by the number of the individual tests performed (O'Brien & Kaiser, 1985). The Bonferroni-adjusted significance levels are reported, when appropriate.

A MANOVA was performed on the RT means (Table 1) with two between-subjects and three within-subject factors. The between-subjects factors were sex (male, female) and heart period (short, long). The within-subject factors were stimulus location (central, right, left), hand (right, left), and cardiac phase (systolic, diastolic).

The significant main effects were those of sex [$F(1,34) = 6.95, p = .013$], stimulus location [$F(2,33) = 73.18, p < .001$], and hand [$F(1,34) = 9.08, p = .005$]. Males had faster RTs (230.7 msec) than females (263.7 msec), and the right hand responded faster (242.7 msec) than the left hand (248.1 msec). Pairwise contrasts showed that RTs for the central stimulus (234.7 msec) were considerably shorter than those for the right (248.8 msec) or the left (252.8 msec) stimuli [$F(1,37) = 88.83, p < .01$, and $F(1,37) = 135.17, p < .001$, respectively]. In addition, right stimuli were associated with faster performance than were left stimuli [$F(1,37) = 7.79, p = .024$].
Among the two-way interactions, the hand $\times$ stimulus location $[F(2,33) = 16.06, p < .001]$, the hand $\times$ cardiac phase $[F(1,34) = 5.14, p = .030]$, the stimulus location $\times$ cardiac phase $[F(2,33) = 4.02, p = .027]$, and the heart rate $\times$ cardiac phase $[F(1,34) = 21.11, p < .001]$ effects proved to be significant.

Analysis of the simple effect of hand within each stimulus location showed that for right hemifield stimuli, the right hand responded faster than did the left hand (right hand, 243.5 msec; left hand, 254.1 msec) $[F(1,37) = 26.58, p < .001]$, and a similar, but only marginally significant, tendency was found for central stimuli (right hand, 232.2 msec; left hand, 237.3 msec) $[F(1,37) = 5.02, p = .093]$. No performance difference between the hands was found for left stimuli (right hand, 252.6 msec; left hand, 237.3 msec) $[F(1,37) = .04, p = .840]$. The most important effects relevant to our main hypothesis were the hand $\times$ cardiac phase and the stimulus location $\times$ cardiac phase interactions. Analysis of simple effects showed that for responding with the right hand, the systolic RT tends to be somewhat longer than the diastolic RT (systolic RT, 244.1 msec; diastolic RT, 241.3 msec) $[F(1,37) = 4.40, p = .086]$, whereas the speed of the left hand’s response was unaffected by the timing of the stimulus within the cardiac cycle (systolic RT, 247.5 msec; diastolic RT, 248.8 msec) $[F(1,37) = .88, p = .356]$. Analysis of the simple effects within each stimulus location yielded only one marginally significant result: RTs tended to be longer when right stimuli were presented during the systolic phase (systolic RT, 250.4 msec; diastolic RT, 247.2 msec) $[F(1,37) = 5.77, p = .063]$. The speed of the reaction was not influenced by the timing of stimulus presentation for either central stimuli (systolic RT, 234.2 msec; diastolic RT, 235.3 msec) $[F(1,37) = .75, p = .392]$ or left stimuli (systolic RT, 252.8 msec; diastolic RT, 252.8 msec) $[F(1,37) = 0, p = .988]$. In regard to our second hypothesis, the highly significant heart rate $\times$ cardiac phase interaction indicated that the effect of cardiac cycle time on RT in subjects with short heart periods was different from that found in subjects with long heart periods. Subjects with short heart periods had quicker responses for stimuli presented during systole (systolic RT, 245.4 msec; diastolic RT, 248.3 msec) $[F(1,18) = 6.84, p = .034]$, whereas the opposite effect was found in subjects with long heart periods (systolic RT, 246.2 msec; diastolic RT, 241.9 msec) $[F(1,18) = 9.65, p = .012]$. However, the sex $\times$ heart rate $\times$ cardiac phase interaction was also significant $[F(1,34) = 7.32, p = .011]$, indicating that males and females differ in this respect. For females there was a strong interaction effect of heart rate $\times$ cardiac phase (systolic RT, 260.9 msec; diastolic RT, 266.1 msec, for short heart period females; systolic RT, 267.3 msec; diastolic RT, 260.4 msec, for long heart period females) $[F(1,15) = 22.79, p < .001]$, whereas for males this effect did not attain significance (systolic RT, 234.1 msec; diastolic RT, 235.3 msec for short heart period males; systolic RT, 227.2 msec; diastolic RT, 225.2 msec for long heart period males) $[F(1,19) = 2.09, p = .328]$. The difference between males and females in RT speed found in this study is in harmony with data presented in the literature (for a review, see Welford, 1980). Whether this difference can be attributed to some fundamental biological factor or it originates from different sex roles is not clear. RTs proved to be longer for both left and right lateral stimuli than for central stimuli. This result is completely in conformity with those of classical (Poffenberger, 1912) and modern (Payne, 1966) studies, and can be explained by the decrease of receptor density with the increase of

### Table 1

**Reaction Time Means ($M$) and Standard Deviations ($SD$) in Milliseconds in the Different Stimulus Location, Responding Hand, and Cardiac Phase Conditions for Males and Females With Fast and Slow Heart Rates**

| Condition          | Males’ Heart Period | Females’ Heart Period |
|--------------------|---------------------|-----------------------|
|                    | Long $M$ | SD $M$ | Short $M$ | SD $M$ | Long $M$ | SD $M$ | Short $M$ | SD $M$ |
| Cs/Rh/Sy           | 222.1    | 39.3   | 213.4    | 28.2   | 249.2    | 37.6   | 254.2    | 50.2   |
| Cs/Rh/Di           | 223.9    | 38.7   | 212.6    | 24.2   | 247.5    | 38.0   | 246.7    | 46.12  |
| Cs/Lh/Sy           | 226.8    | 50.0   | 212.6    | 25.6   | 250.3    | 35.9   | 257.7    | 39.2   |
| Cs/Lh/Di           | 231.4    | 48.9   | 213.8    | 31.4   | 259.7    | 37.0   | 258.9    | 40.5   |
| Rs/Rh/Sy           | 234.4    | 38.0   | 232.7    | 27.5   | 255.2    | 33.8   | 264.8    | 50.4   |
| Rs/Rh/Di           | 228.3    | 32.2   | 226.2    | 27.7   | 265.4    | 45.0   | 253.0    | 49.1   |
| Rs/Lh/Sy           | 243.2    | 41.8   | 234.4    | 25.0   | 275.6    | 37.1   | 275.1    | 42.0   |
| Rs/Lh/Di           | 242.5    | 49.2   | 230.4    | 29.2   | 276.3    | 36.4   | 270.2    | 47.0   |
| Ls/Rh/Sy           | 239.0    | 36.4   | 235.0    | 31.4   | 268.3    | 45.3   | 279.9    | 62.7   |
| Ls/Rh/Di           | 240.6    | 35.3   | 234.1    | 30.6   | 271.7    | 36.4   | 265.4    | 52.1   |
| Ls/Lh/Sy           | 239.3    | 49.8   | 235.0    | 25.6   | 266.7    | 33.3   | 272.4    | 42.8   |
| Ls/Lh/Di           | 245.0    | 45.4   | 234.1    | 29.1   | 276.3    | 47.0   | 268.1    | 50.0   |

Note—Cs, Rs, Ls, central, right, and left stimulus; Rh, Lh, right and left hand; Sy, Di, systolic and diastolic stimulus presentation.
distance from the fovea (Österberg, 1935). Regarding the performance difference between the hands, the right-hand advantage found in this study is also in agreement with the results of the majority of simple RT studies (see the meta-analysis of Marzi, Bisiacchi, & Nicoletti, 1991). Less typical was the finding that RTs were shorter for right than for left stimuli. In other simple RT studies, a left visual field advantage has been reported usually (but not invariably) (Marzi et al., 1991).

The anatomical relationships of the retinæ and the hands well explain the interaction obtained between stimulus location and hand. It has been known for a long time that anatomically uncrossed simple reactions are a few milliseconds faster than crossed reactions due to the callosal transfer time (Berlucchi, Heron, Hyman, Rizzolatti, & Umlitá, 1971; Poffenberger, 1912). In our experiment, the average time difference between ipsilateral and contralateral responses turned out to be 5.1 msec, similar to the values obtained in earlier studies (for a review, see Swanson, Ledlow, & Kinsbourne, 1978). (The right-hand–left-hand difference was greater for right stimuli by 5.5 msec, and smaller for left stimuli than for central stimuli by 4.7 msec.)

The main hypothesis of this experiment concerning the laterality of cardiac phase effects on RT was not confirmed. As expected, the sensorimotor functions of the two hemispheres did seem to be differentially influenced by cardiac activity, as shown by the hand × cardiac phase and stimulus location × cardiac phase interactions. However, this effect was weak and, contrary to our initial assumption, left hemispheric sensorimotor functions tended to depend to a greater degree on the timing of the stimulus within the cardiac cycle. Specifically, it was true only for right visual stimuli and for the right hand that responses were marginally faster when the stimulus was applied in the diastolic phase as compared to the systolic phase; the cardiac phase effect was absent for left stimuli and for the left hand.

On the basis of earlier heartbeat perception and heart-beat evoked potential studies, we expected that cardiac activity would have a greater impact on right hemispheric sensorimotor activities than on activities of the left hemisphere. In the only study that addressed a question similar to ours (Walker & Sandman, 1982), right hemispheric sensory functions were found to be more sensitive to cardiac phase effects than those of the left hemisphere when EEG measures were used. (It must be noted, however, that the authors themselves discussed the potential role of some confounding factors that might have resulted in a pseudo-lateralization of evoked potentials. The most important problem they mentioned was that “since the heart is asymmetrical, electrical activity from the heart could spread asymmetrically to the two hemispheres and summate with the evoked potentials”; Walker & Sandman, 1982, p. 525.) Our behavioral findings do not support the assumption that cardiovascular afferents exert a greater influence on the right hemisphere; if anything, they suggest a left hemispheric effect. However, because this effect was small and only marginally significant, and it is in conflict with the implications of earlier studies, other experiments are needed to substantiate its existence.

Regarding our second hypothesis, we found that the length of the heart period greatly determines the direction of the cardiac phase effect. Subjects with long heart periods displayed the expected effect of cardiac phase; namely, their RTs were longer in the systolic than in the diastolic phase. Conversely, subjects with short heart periods showed the reverse effect: Their RTs were longer in the diastolic phase. The modulating effect of heart period was significant only for females, but the tendency was similar also for males. The two hemispheres did not differ in this respect.

Two points should be mentioned in connection with the above result. First, it may well be that the failure to take into account the effect of heart period length might explain the negative findings in some of the earlier RT and detection experiments. Had we not entered heart period into the statistical analysis, we also would not have found any effect of cardiac phase on RT. Although many investigators have reported that RT was shortest during diastole, Wynn (1980) mentioned that in her one-case study the maxima and minima of RT fluctuations were located in different places within the cardiac cycle during different sessions. We know of only one earlier study that investigated the effect of heart rate in a similar RT experiment (Coles et al., 1982). They did not find any difference between slow and fast heart rate subjects; however, they had only 5 subjects in each heart rate group, and all of them were males.

Second, the reverse cardiac phase effect demonstrated in the short heart period group is not necessarily inconsistent with the Laceys’ (1970) baroreceptor hypothesis. A possible interpretation for this finding might be that in short heart period subjects, the later stages of the processing of diastolic stimuli and motor preparation may often take place during the early phase of the subsequent cardiac cycle, that is, during the systolic phase, whereas in long heart period subjects, not only the stimulus presentation, but also all stages of information processing and response preparation occur during the diastole. Thus, on the basis of the Laceys’ hypothesis, only long heart period subjects would be expected to have shorter RTs during diastole, whereas short heart period subjects would be expected to have variable direction and degree of the difference between systolic and diastolic RTs. Callaway and Layne (1964) suggested that cardiac phase might exert its effect on the later stages of sensory processing and on motor preparation, raising the possibility that the cardiac phase effect would depend not on the timing of stimulus presentation but on the timing of the response within the cardiac cycle. The results of Saari and Pappas (1976), however, indicated that cardiac cycle is more closely correlated with afferent rather than efferent processes.

Why only females displayed the dependence of the cardiac phase effect on heart period length cannot be answered on the basis of these results. Since males, as a group, had shorter RTs than did females, the question arose whether the observed sex difference might actually be a difference between quick and slow responders. Post hoc analyses, however, did not support this assumption.

The main finding of this experiment was that sensorimotor functions of the left hemisphere tended to be af-
fected to a greater degree by physiological changes associated with the cardiac cycle than did those of the right hemisphere. Additionally, the effect of cardiac phase on RT differed depending on heart period length, at least for females. Although the modulating effect of heart period length might have a simple—although to be tested—explanation that conforms with the Laces’ (1970) hypothesis, the origin of the sex difference is unclear. In any case, the results of this experiment underline the importance of the use of heart rate and sex as modulating variables in the future cardiac cycle time effect experiments.

It is necessary to emphasize the limitations of our approach, which are common to reaction time, detection, and evoked potential studies. First, the cardiac cycles are accompanied not only by cyclical baroreceptor activity changes but also by concomitant variations of blood vessel dilatation within the brain, movement of tissue in the vicinity of the blood vessels, and fluctuations in O2 supply. In the cardiac cycle time experiments, the latter variations cannot be separated from baroreceptor activity changes and, consequently, the role of baroreceptor activity in the observed behavioral or electroencephalographic changes cannot be unequivocally substantiated. Forster and Stone (1976), for example, argued that cardiac phase dependent modulation of finger tremor is related to the effect of blood movement on spinal cord excitability. However, at present no noninvasive method is available for assessing the effects of naturally occurring baroreceptor activity changes separately. Besides, although baroreceptor activity can be experimentally manipulated in humans, the above criticism holds, at least in part, also for the newest manipulative technique (Rau, Elbert, Geiger, & Lutzenberger, 1992). This technique is able to produce profound baroreceptor activation and deactivation, but these changes are also inseparable from variations in blood vessel diameter and O2 supply. In our opinion, in spite of the interpretational problems, such studies seem to be worth pursuing, because—at least on a phenomenological level—they might provide new information about the interrelationship of cardiovascular and brain processes.

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**NOTE**

1. Elliott and Graf (1972), who used a stimulus detection task, presented the individual hit rates of their subjects during different phases of the cardiac cycle in their paper. Although they were unable to find any systematic variation in hit rate between the four conventional cardiac phases QRS, T, T-P, P, a reanalysis of their data shows that the mean of the absolute values of the hit rate difference between the QRS and P phases was significantly greater than that between the T and T-P phases or the P and T-P phases. In the case of no cardiac cycle time effect, the absolute values of all these differences are expected to be equal. This result, however, suggests that for some subjects the hit rate was considerably higher, and for others, it was considerably lower during the QRS phase than during the P phase of the cardiac cycle.

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