

Effects of Feedback Delay and Feedback Timing upon Voluntary Heart Rate Control

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Summary Two experiments were conducted to examine the effects of feedback delay during voluntary heart rate (HR) control and to test whether feedback display timing must be synchronized with R-wave of the cardiac cycle. Subjects were required to put their HR as much as possible into the 40 ms wide target zone under various conditions: Immediate, R-desynchronized (1/2-variable delay), 1-beat delay, 3-beat delay and No feedback in Experiment 1, and Immediate, 1-beat delay, 1/2-constant delay and 1/2-variable delay in Experiment 2. Results indicated that very short delay of feedback can disturb the performance of voluntary HR control, and that the disturbed performance for the R-desynchronized condition was due to the half-beat delay of feedback. The findings supported the analogy between motor skills learning and voluntary HR control.

Key words: Delayed Feedback; Heart Rate; Perceptual Motor Skill

In many reports, investigators have attempted to understand the development of voluntary HR control through biofeedback from the viewpoint of motor skills learning¹⁻³⁾. So far, it has been reported that HR speeding is systematically influenced by some feedback parameters which, in turn, also influence the performance in motor skills learning^{4,5)}.

Although there are many variables which affect the performance of feedback control in closed-loop systems, the feedback delay, or the time lag, between a response and feedback information is a particularly critical parameter. The detrimental effects of delayed feedback on the performance of various types of motor

skills learning have been repeatedly observed⁶⁻⁸⁾, in which a very short delay of less than 1 s has been shown to seriously disrupt continuous motor responses.

In the area of biofeedback, Williamson and Blanchard⁹⁾ examined the effects of feedback delay upon bidirectional HR control. They compared the magnitude of HR increase and decrease between subjects who received immediate feedback and those that received feedback delayed by 1.4 s, 5 s, or 14 s. In their study, although detrimental effects were identified according to the length of feedback delay on both increase and decrease of HR, significant differences in both HR changes were obtained only between immediate and 14-s delay groups. Thus, much longer feedback delay was required to disrupt control

performance in comparison with motor skills learning. Williamson and Blanchard⁹⁾ attributed the cause of this discrepancy to the difference in response modalities. They described that successive IBIs were so correlated that the subjects' perceived difference of information between the immediate feedback and the short time delay feedback might have not been strong enough to affect performance.

Presence/absence of a target, or a goal, is another important difference between a motor task, such as tracking, and an HR control task. In the tracking task, contained in feedback information is a degree of error defined in terms of direction and specific magnitude of change required for attaining the target. In contrast, almost all experiments of voluntary HR control, including Williamson and Blanchard⁹⁾, required subjects to increase or decrease their sustained HR as much as possible without providing them with a clear target. Feedback information is characteristically negative in the closed-loop feedback control system, except in some special cases. It therefore seems that tasks more similar to motor learning tasks, in which feedback information shows the degree of error toward the target, are needed in order to further examine the properties of feedback in the closed-loop system.

Delayed feedback is likely to cause low-frequency oscillation resulting from over-correction. Because feedback of information is delayed, correction of the identified error is continued beyond what is required, giving rise to another error in the direction opposite of that of the previous one, as a result. Likewise, the subsequent attempt to correct this new error generates yet another error, and so on. Because unnecessary correction is repeated in this way, the more accurate the control and the longer the delay, the greater becomes the degree of errors, which eventually leads to low-frequency oscillation.

Although Johnston¹⁰⁾ tried to prove, through HR or blood volume increasing or decreasing tasks, the theory which holds that biofeedback aided learning is analogous to motor skill learning, he was unable to obtain a distinct evidence. However, when Johnston and Lethem⁴⁾ examined effects of feedback mode, feedback frequency, and so on, using a technique whereby the subject was required to increase HR by a small specific amount, most of their results supported the analogy between voluntary autonomic response and motor skills learning.

Inamori¹¹⁾ examined the effects of 3-beat delayed feedback on voluntary HR control where target zone was 50 ± 20 ms or -50 ± 20 ms from pre-trial baseline inter beat interval (IBI). The first group of subjects initially received immediate feedback trials, and later, 3-beat delayed feedback trials. The second group of subjects received immediate feedback trials after they received 3-beat delayed feedback trials. Results partly indicated that feedback delay disrupted the accuracy of HR control and that feedback delay caused low-frequency oscillation in HR variability. Because the subjects' variance of performance was so large, short delays of 3 or so beats did not clearly show the effects of feedback delay in between-subjects experiment.

The primary purpose of the present experiment was to closely examine the effects of 3-beat or less than 3-sec feedback delay on HR control task in within-subjects experiment. The task was to track, not a fixed target, but the target way of a biphasic triangle wave.

Another purpose of this experiment was to examine whether it is necessary for HR feedback to synchronize with the R-wave of ECG. Brener¹⁾ considered calibration between internal feedback and external biofeedback as a very important factor for the voluntary control of autonomic responses in his model. According to this

model, while self-perception of internal feedback was indeed essential, self-perception of HR was found to be facilitated by learning¹²⁾. While many investigators have since examined the possibility of self-perception of either HR or heart beat^{9,13)}, it remains uncertain whether subject perceive specific temporal information, such as, the occurrence of heart beats¹⁴⁾, or some information of performance change, such as, the change in HR. Both types of information are involved in the case of pulse trains. Lang & Twentyman⁵⁾ and Twentyman¹⁵⁾ found that the task performance of HR increase was extremely lower in 1-s or 2-s fixed time feedback conditions not synchronize to R-wave on ECG. They attributed the lower task performance to the absence of temporal information in the fixed time feedback in cases where systole occurred. However, also included in the fixed time feedback they used were various feedback delays of less than 1 s. Moreover, it is possible that the monotony of fixed interval feedback have disturbed the subjects' task performance. It is not known whether the performance deterioration they observed was due to the absence of specific temporal information or to other factors, such as, feedback delay or the constancy of feedback presentation.

Experiment 1

Method

Subjects

Seven male and 7 female undergraduates served as subjects. The ages ranged from 20 to 23. None of them reported heart disorders. They were paid a monetary reward in the manner described below.

Apparatus

An electrocardiogram (ECG) from subject's right leg and left ear robe was

recorded with a preamplifier (Nihon-koden: RB-5) and transmitted to digital logic modules. The logic modules and micro-computer system (SORD M-100 ACE) automatically controlled the detection of the R-wave on the ECG, counting the R-R interval, initiation and termination of each trial, primary data reduction, and display and manipulation of feedback and target stimuli. The resolution error of counting the R-R interval was less than 2 ms. A CRT display to present the feedback and the target stimuli was placed about 1.5 m in front of the subject.

Procedure

Subjects were comfortably seated in a reclining chair in a sound-attenuated, shielded chamber. After having the electrodes attached, a demonstration of the feedback system was given, and subjects were fully instructed about their tasks and the nature of the feedback stimulus, but they were not instructed about the delayed feedback condition. They were also told that they could do anything for their task execution, providing it did not disturb the HR measuring.

After a 5-min rest period, 100-interbeat intervals (IBIs) were measured at initial criterion, and followed by 4-practice trials and 20 trials consisting of 100 IBIs. During the trial the target and HR feedback of each beat were presented on the CRT display. The subject's task was to try to keep their HR in the target area as much as possible. The target was a cycle triangle wave of 40-ms vertical width (see Figure 1). The beats within the target area was accumulated as a score. After the experiment, the subject was paid yen/score +500 yen. Five types of feedback conditions were used in this experiment: Immediate feedback (IM), R-desynchronized feedback (RD), 1-beat delayed feedback (1D), 3-beat delayed feedback (3D), and No feedback (NF) conditions. In all conditions, except

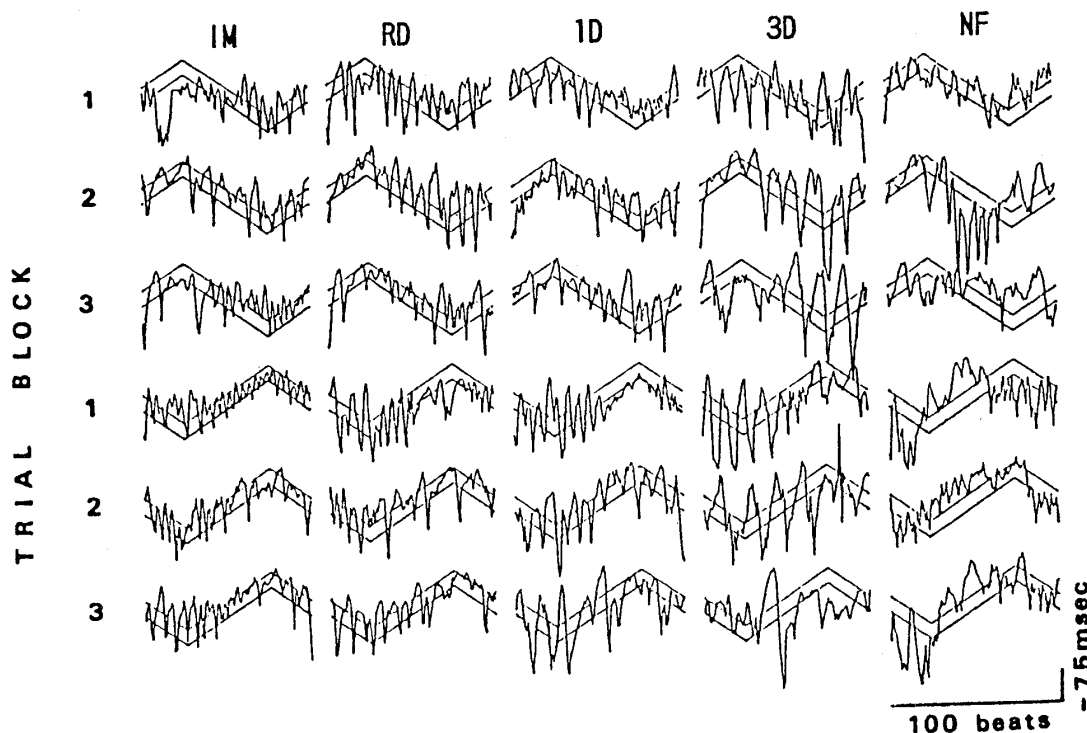


Fig.1. IBI changes and targets of all trials from one subject.

for NF, the feedback dot moved to its new position, which was horizontally one point to the right and vertically proportional to the IBI, immediately after the ECG R-wave was detected. A click from a speaker signaled the change in the feedback dot position. The position of each HR feedback was proportional to the newest IBI of the IM trials. But in the 1D and 3D trials, the position was proportional to the computer stored IBI of 1-beat or 3-beat earlier. In the RD condition, the position of each HR feedback was proportional to the newest IBI, and it was presented just after the R-wave of a data recorder (TEAC RD-260) which stored ECG of 4.6 s earlier. The 4.6-s delay time was obtained on the basis of the distance between a recording head and a re-product head of the data recorder. Thus, the feedback in RD condition had random delay time of less than a beat.

The first target was set at S's median IBI for the 100 beats of pre-practice trial, and for each trial the mean of median IBI and target IBI of the last trial was adopted as

the new target for each trial. Inter-trial-interval was 25 IBIs, and a score of the previous trial and an accumulated score were displayed on the CRT.

Spectrum analysis

In general, the detrimental effects of delayed feedback are expected to generate low frequency oscillation in the control system. So HR variabilities were examined by frequency analysis using Fast Fourier Transform (FFT). At first, a hundred IBIs of a trial were transformed by Z-score ((each IBI - mean IBI) / standard deviation). The first and last 10 percent of each 100-IBIs segment were tapered off by a smooth cosine window to avoid possible abrupt discontinuities at the ends of the record. In order to form 128-points data, 28-zero data were added. After FFT, the spectral values were smoothed by a Hanning window.

Results

None of the subjects reported in the post-experiment interviews that they

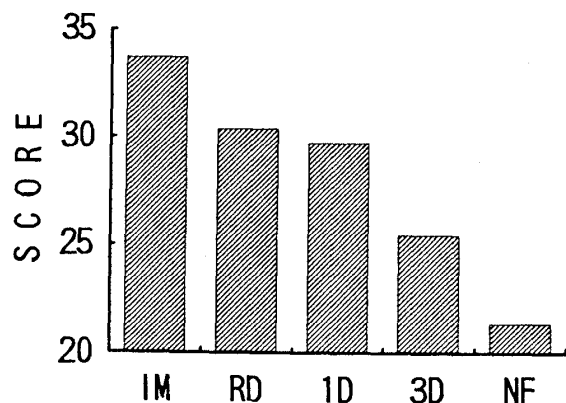


Fig. 2. Mean score for five feedback conditions.

noticed the delayed feedback conditions. Although some of them reported that some trials were difficult to execute, they could not explain the reasons for the difficulty.

A raw data from a typical subject were presented in Figure 1. In IM condition, IBIs tracked the target fairly well, but in other conditions, the tracking performances decreased progressively in the order of RD, 1D, 3D, and finally, NF condition. A particularly large HR variable were in 3D condition indicated a kind of oscillation which occurred in HR control system caused by the delayed feedback signal failing to serve as negative feedback. The same phenomenon was also observed in the data on many of the other subjects.

Mean scores, or the beats in target per trial, for all of the five conditions are presented in Figure 2. The scores for RD and 1D conditions were lower than that for IM condition but higher than the score for 3D feedback condition. The score for NF feedback condition was the lowest. Three way repeated measure analyses of variance (ANOVA) with 5-feedback conditions, 3-trial blocks, and 2-target types was carried out. A significant main effect of feedback conditions was obtained ($F(4/52)=25.52$). Post-hoc analyses indicated that the score of IM condition was the highest, the scores of RD and 1D were close and were

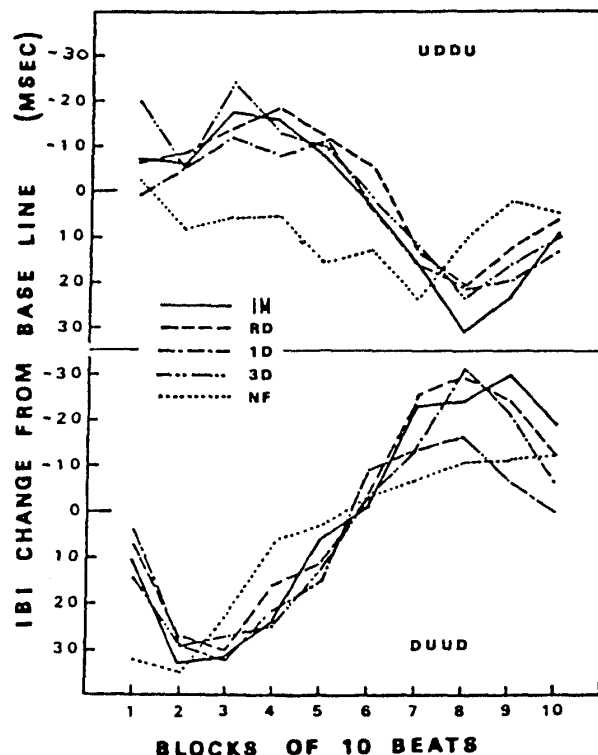


Fig. 3. Mean changes in IBI from baseline level for five feedback conditions. UDDU target trials are shown in the top panel, and DUUD target trials are shown in the bottom panel.

both higher than those of 3D and NF conditions, and that the score of 3D condition was higher than that of NF condition. No difference was found among different trial blocks. Moreover, the score of DUUD target trial was found higher than that of DUUD target trial. These results then, show that very short delay of the feedback can disturb the performance of voluntary HR control.

While the same ANOVA was conducted on mean IBIs during trial, no significant Fs were obtained. Furthermore, as illustrated in Figure 3, the mean changes for 10 IBIs showed little difference among the five feedback conditions. These results show that, regardless of feedback conditions,

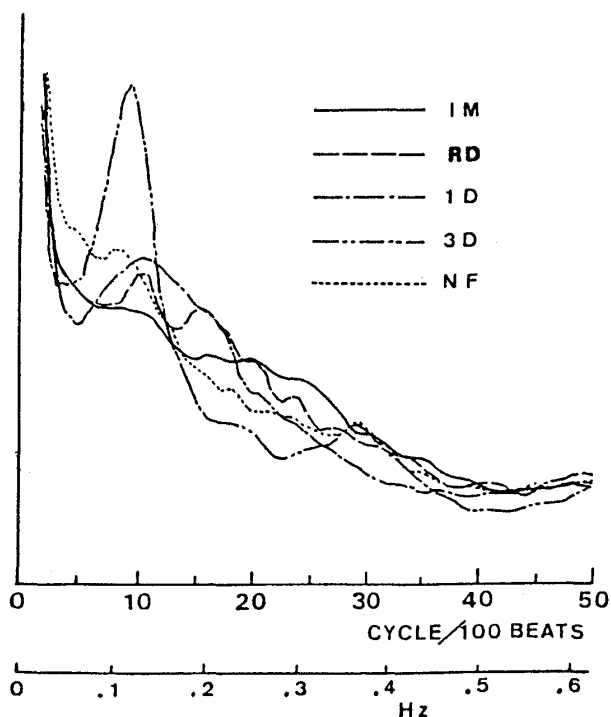


Fig. 4. Mean power spectrum for five feedback conditions.

subjects could increase and decrease their HR roughly according to the given target direction.

Illustrated in Figure 4 are the mean power spectrums for the five feedback conditions. X-axis represents not Hz but cycles/trial (c/t). As can be seen, a clear peak of power is observed around 10 c/t for delayed feedback conditions, particularly for 3D condition. When the powers between 12th and 14th harmonic numbers (or 9.38 -10.94 c/t frequency band), were compared, the power of 3D condition was larger than all other conditions (sign test, $p < .01$), and the power of 1D condition was larger than IM or RD conditions (sign test, $p < .05$). These results indicate that delay feedback caused low-frequency large-amplitude oscillation in HR variability.

Discussion

The task designed for this experiment

was a perceptual motor task of target tracking using HR instead of subject's hand movement. It was originally expected that the one-beat delay would not disturb the task performance, and therefore, 1D was initially regarded as a control condition for the RD condition. The results, however, indicated that not only 3D but also 1D could disturb the task performance.

Although the disturbed performance was seen in RD condition, it was not possible to determine whether it was due to R-desynchronized effect itself or to the delayed feedback effect of less than one-beat. If one-beat delay had no effect, the disturbed performance of RD condition could be concluded as being affected by R-desynchronized timing. In RD condition, each piece of feedback information was presented not only in R-desynchronized timing, but also with various delays of up to one-beat. To clarify this point, further research is necessary.

Experiment 2

Two conditions, the one was 1/2-variable delay and the other was 1/2-constant delay, were compared. Since the R-desynchronized condition, or 1/2-variable delay condition, involved an R-desynchronized factor and a delay factor, it was necessary to separate these factors by adding 1/2-constant delay condition in this experiment. It was expected that the delay time of 1/2-constant condition and the delay time of 1/2-variable condition would be approximately same.

Method

Subjects

Eight male and 8 female undergraduates aged between 20 and 23 served as subjects. None of them reported heart disorders. They were paid a monetary reward in the same manner as in Experiment 1.

Procedure

Physiological measuring and fundamental procedure were the same as in Experiment 1. ECG was recorded from the right ankle and left ear robe. By employing a microcomputer, to which the R-wave of ECG was transmitted the IBI fro every beat was displayed on CRT screen as feedback. Also displayed on the screen was the target, into which subjects were instructed to put as many IBI's as possible. While subjects were given thorough instructions about their task, the feedback was described to them as being immediate feedback following R-wave. Four types of feedback were used: Immediate feedback (IM), 1/2-constant delay feedback (1/2CD), 1/2-variable delay feedback (1/2VD), and 1-beat delay feedback (1D) conditions. The delay time of 1/2CD was equivalent to half of the median IBI for the 100 beat of the last trial. The 1/2VD condition was the same as the R-desynchronized condition in Experiment 1.

Two sessions, each consisting 16 trials, of 4 conditions x 2 type of target (UDDU vs DUUD) were conducted. There were 2-min rests between sessions. Four practice trials of IM condition were added at

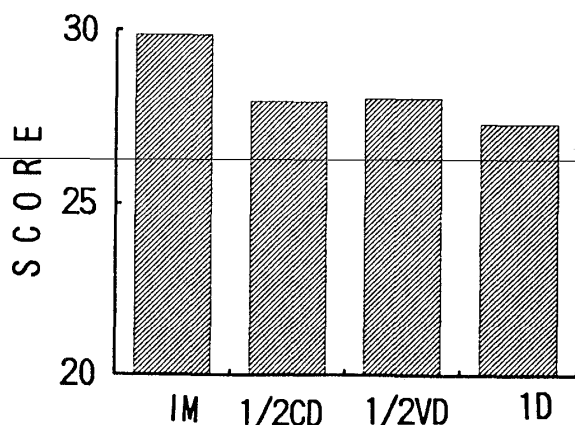


Fig. 5. Mean scores for four feedback conditions.

the beginning of the first session, and two practice trials were added at the beginning of the second session.

Results

None of the subjects reported that he or she noticed delayed feedback conditions. The mean delay time of 1/2CD and 1/2VD conditions were respectively 403 ms and 399 ms each, which satisfied the premise of maintaining the mean delay time of the 1/2-beat delay conditions approximately equal.

First of all, it must be noted that mean median IBIs for all the trials were almost equivalent for all conditions (IM:809, 1/2CD:804, 1/2VD:813, and 1D:810 ms).

Figure 5 indicates mean scores, or beats on target, for each condition during trial which consisted of 100 beats. The ANOVA indicated that the score for IM condition was significantly higher than the score for 1D condition ($F(1/45)=5.61$, $p<.025$) and also tended to be generally higher than those for the other two conditions. The scores for 1/2CD and 1/2VD conditions were approximately the same, indicating that the deterioration of score for 1/2VD condition in comparison to IM condition was not due to the desynchronization of feedback timing but to the feedback delay of an average of around 400 ms.

Figure 6 indicates mean power spectrums. As can be seen, the power distributions of 1/2CD and 1/2VD conditions were quite similar in all frequency bands and were located between the power distributions for IM and 1D conditions. As in experiment 1, the power is enhanced at around 10 c/t. At 9-11 c/t, the power for 1D-condition was significantly greater than for 1/2CD- and 1/2VD-conditions, and the power for 1/2CD- and 1/2VD-conditions were larger than that for IM-condition. These results indicate that there are no differences at all between 1/2CD- and

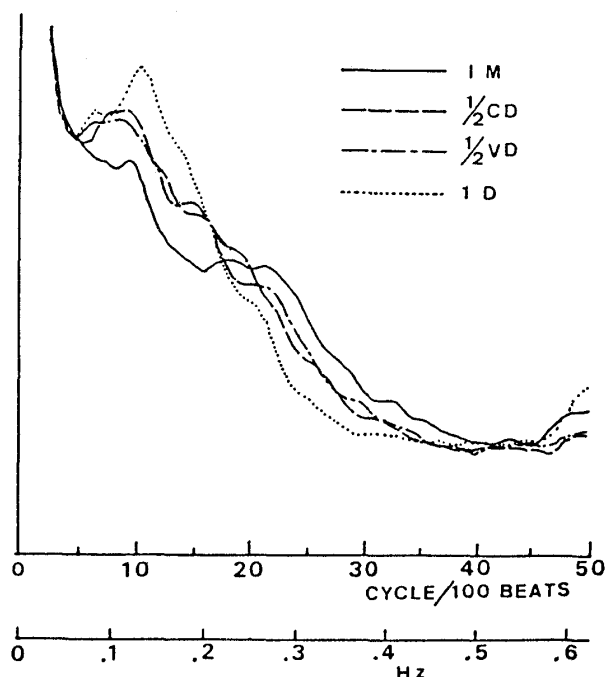


Fig. 6. Mean power spectrum for four feedback conditions.

1/2VD-conditions. The power spectrum distribution, on the other hand, is affected by delay conditions: the longer the delay, the more enhanced is the power in low frequencies.

General discussion

The first purpose of this experiment was to examine the effects of feedback delay upon voluntary HR control task. Apparent effects of feedback delay could be identified. In experiment 1, the 3D feedback clearly impaired task performance, or beats in target, which may be explained by the possible occurrence of low-frequency and high-magnitude oscillation on HR variations. The disturbing effects for 1D condition were also observed in both experiments, perhaps caused by a mechanism similar to that of 3D effect. Moreover, the scores for both 1/2CD and 1/2VD conditions were found at midpoint between

1M and 1D conditions. Thus, the results on feedback delay of this experiment indicate that the task performance declined as a function of feedback delay, and that low-frequency high-amplitude oscillation of HR occurred accordingly. These effects of delayed feedback suggest that the voluntary HR control involves a closed circuit system, in which the feedback is working negatively and information is flowing at a fairly high rate. These characteristics are also seen in motor learning systems and servo mechanisms in machine systems.

Compared to Williamson and Blanchard⁹⁾, the present results show that much shorter temporal delays also affect task performance of HR control. Williamson and Blanchard⁹⁾ described that the effect of feedback delay seen in motor skills learning was absent in the case of HR control task because of the high correlations of successive IBIs minimizing the difference between delayed and immediate feedback information, thus, preventing short delay feedback from affecting performance of HR control task. Their explanation, however, was not applicable to the results of the present experiments, in which the feedback information of the 1/2-beat delay was the same as that of immediate feedback. The different effects of delayed feedback observed in Williamson and Blanchard⁹⁾ and motor skills tasks might not be due to the difference in response modalities between motor response and autonomic response but to the difference in the nature of tasks required. The task in the present experiments was like a pursuit tracking task, while the task in Williamson and Blanchard⁹⁾ was a purely directional task which required subjects to make directional changes as much as possible. Johnston and Lethem⁴⁾, who adopted a target in the form of a zone as in the present experiment, have discussed this point in detail.

In a purely directional task, what investigator evaluates may not be in accord with what feedback indicates. While investigator evaluates mean HR in assessing the success of task performance, beat-by-beat feedback does not give mean HR. It is very difficult for subjects to estimate mean HR and to know the degree of success of their task performance by receiving beat-by-beat feedback. The feedback which most closely approximates the investigator's evaluation would be a feedback represented by an accumulated mean HR covering from the beginning of a trial up to respective IBIs. These types of feedback, however have not yet been used so far. If the role of feedback is only to indicate mean HR, low-frequency feedback showing mean HR should be better than beat-by-beat feedback. However, the results of many experiments showed that the performance with low-frequency feedback was worse than that with high-frequency feedback^{16,17)}. This may be explained by the difference in the nature of strategy adopted by the subject. One study showed that while subjects could increase their HR by increasing either their breathing or muscle activities, subjects' ability to accelerate HR was weakened when the use of these strategies was restricted¹⁸⁾. The restriction on the use of such strategies, however, were ambiguous in many of the purely directional experiments. Although subjects were instructed to breathe as normally as possible and avoid muscle tension or movement, the data was discarded only when there were very remarkable respiratory confusions or body movements. Under such circumstances, it is up to subjects to decide to what extent they will use those meditative strategies to control autonomic nervous activities. It therefore follows, as is reported by some, that subjects with high ego strength scores are best able to control their HR¹⁹⁾. Many investigators reported that real time continuous analogue

feedback was the most effective in increasing HR. This is probably because continuous feedback, which clearly feeds back the effect of a strategy, i.e. the changes made in respiration or in muscle tension, facilitates the subjects' task of calibrating the effect to HR change.

The second purpose of the study was to examine whether it is necessary to synchronize the timing of feedback presentation with the R-wave on the ECG. The result of the second experiment indicated that the synchronization was not necessary for the task. The conditions of 1/2CD and 1/2VD were the same except that feedback delay time was constant in the former but variable in the latter. The task performance and the distribution of power spectrum for the two conditions were equivalent, and they were both located midway between IM and 1D conditions. Whether feedback presentation timing was synchronized with R-wave or not had no effect, and only the effects of feedback delay were reflected in the present results. The reason for the better performance in IM condition than in any other conditions then lied not so much in the R-synchronized presentation but in the minimum feedback delay.

In conclusion, the results of the present experiments indicated that very short feedback delay disturbs task performance on voluntary HR control, and it is not necessary to synchronize feedback presentation with R-wave in ECG. The results support the view that voluntary HR control involves a control mechanism similar to that of motor skills learning.

Reference

1. Brener, J. 1974 A general model of voluntary control applied to the phenomena of learned cardiovascular change. In P.A. Obrist, A.H. Black, J. Brener., & L.V. DiCara (Eds.), Cardio-

- vascular psychophysiology. Chicago: Aldine, Pp. 365-391.
2. Lang, P.J. 1974 Learned control of human heart rate in a computer directed environment. In P.A. Obrist, A.H. Black, J. Brener., & L.V. DiCara (Eds.), Cardiovascular psychophysiology Chicago: Aldine, Pp. 392-405.
 3. Schwartz, G.E. 1974 Toward a theory of voluntary control of response patterns in the cardiovascular system. In P.A. Obrist, A.H. Black., J. Brener., & L.V. DiCara (Eds.), Cardiovascular psychophysiology Chicago: Aldine, Pp. 406-440.
 4. Johnston, D.W., & Lethem, J. 1981 The production of specific decreases in interbeat interval and the motor skills analogy. *Psychophysiology*, 18, 288-300.
 5. Lang, P.J., & Twentyman, C.T. 1976 Learning to control heart rate: Effects of varying incentive and criterion of success on task performance. *Psychophysiology*, 13, 378-385.
 6. Conklin, J.E. 1957 Effects of control lag on performance in a tracking task. *Journal of Experimental Psychology*, 53, 261-268.
 7. Kao, H.S.R. 1977 Effects of delay of feedback and intermittency of feedback in compensatory tracking. *Perceptual and Motor Skills*, 44, 1079-1085.
 8. Smith, K.U., & Sussman, H. 1969 Cybernetic theory and analysis of motor learning and memory. In E.A. Bilodeau & I.M. Biloduar (Eds.), *Principles of skill acquisition* New York: Academic Press, Pp. 103-139.
 9. Williamson, D.A., & Blanchard, E.B. 1979 Heart rate and blood pressure biofeedback : I. A review of the recent literature. *Biofeedback and Self-Regulation*, 4, 1-34.
 10. Johnston, D.W. 1977 Biofeedback, verbal instructions and the motor skills analogy. In J. Beatty, & H. Legewie (Eds.), *Biofeedback and behavior* : New York, Plenum, Pp.331-341.
 11. Inamori, Y. 1984 Effects of 3-beat delayed feedback upon voluntary heart rate control. *Japanese Journal of Physiological Psychology and Psychophysiology*, 2, 1-11. (In Japanese with English abstract)
 12. Brener, J., & Jones, J.M. 1974 Interoceptive discrimination in intact humans: Detection of cardiac activity. *Physiology and Behavior*, 13, 763-767.
 13. Carroll, D. 1977 Cardiac perception and cardiac control: A review. *Biofeedback and Self-Regulation*, 2, 349-369.
 14. Whitehead, W.E., Drescher, V.M., Heiman, P., & Blackwell, B. 1977 Relation of heart rate control to heart-beat perception. *Biofeedback and Self-Regulation*, 2, 371-392.
 15. Twentyman, C.T. 1979 Three experiments on the effects of information frequency and feedback training on instructed heart rate speeding. *Journal of Biological Psychology*, 8, 1-29.
 16. Gatchel, R.J. 1974 Frequency of feedback and learned control of heart rate. *Journal of Experimental Psychology*, 103, 274-283.
 17. Twentyman, C.T., & Lang, P.J., 1980 Instructed heart rate control : Effects of varying feedback frequency and timing. *Biofeedback and Self-Regulation*, 5, 417-426.
 18. Vandercar, D.H., Feldstein, M.A., & Solomon, H. 1977 Instrumental conditioning of human heart rate during free and controlled respiration. *Biological Psychology*, 5, 221-231.
 19. Stephens, J.H., Harris, A.H., Brady, J.V., & Shaffer, J.W. 1975 Psychological and physiological variables associated with large magnitude voluntary heart rate changes. *Psychophysiology*, 12, 381-387.