ACQUISITION, DISCRIMINATIVE STIMULUS CONTROL, AND
RETENTION OF INCREASES/DECREASES IN BLOOD
PRESSURE OF NORMOTENSIVE HUMAN SUBJECTS¹

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The aims of this study of 24 normotensive subjects were: to compare a free-operant with a discrete-trials training format; to determine the most effective training procedure by comparing instrumental conditioning with instructional set and a control; to see if both increases and decreases in blood pressure could be brought under discriminative control, and to examine the maintenance of acquired self-control of blood pressure. A 2×3 design was employed in which two trial formats (free operant and discrete trials) were factorially compared with three training conditions (instrumental conditioning, instructional set, and control). Instrumental conditioning was found superior to both the instructional set and control conditions in producing increases and decreases in mean diastolic blood pressure. The free-operant format led to a greater degree of learned BP control in that subjects were able to increase and decrease their blood pressure by 10% to 15% of basal value and to maintain the blood-pressure operant after contingent auditory feedback/reinforcement was removed. Training was discontinued when subjects in the other five groups failed to reach criterion after 10 consecutive acquisition sessions.

DESCRIPTORS: biofeedback, visceral learning, blood pressure, conditioning, instrumental control, humans

It has been asserted that human subjects may be trained to control their blood pressure (Benson, Shapiro, Tursky, and Schwartz, 1971; Blanchard, Young, and Haynes, 1975; Brener and Kleinman, 1970; Elder and Eustis, 1975; Elder, Leftwich, and Wilkerson, 1974; Elder, Ruiz, Deabler, and Dillenkoffer, 1973; Kristt and Engel, 1975; Miller, DiCara, Soloman, Weiss, and Dworkin, 1970; Richter-Heinrich, Knust, Muller, Schmidt, and Sprung, 1974; Shapiro, Schwartz, and Tursky, 1972; Shapiro, Tursky, Gershon, and Stern, 1969; Shapiro, Tursky, and Schwartz, 1971). The basic strategy has been to view blood pressure (BP) as instrumental behavior, and to condition increases and/or decreases as one might shape a skeletal response.

Progress in delineating the active principles involved has been slow, however, because the traditional method for measuring blood pressure (BP) developed by Riva-Rocci almost a century ago (1896) is not readily conducive to instrumental acquisition. A continuous method is preferred and several are in use (Miller *et al.*, 1970; Shapiro, *et al.*, 1969; Tursky, 1974).

More recently, Elder, Longacre, Welsh, and McAfee (1977) devised a system that combines the Shapiro *et al.* and Tursky operation of detecting the K sound threshold with Miller *et al.*'s tracking procedure. A cuff is fitted to each arm and systolic or diastolic BP can be measured on a nearly continuous basis. This development makes it possible to view the BP response as a free operant, and to condition subjects to control it by providing them with a continuous feedback signal, which changes in pitch whenever cuff pressure is readjusted.

However, these developments raise several questions including, first, the comparative efficacy of a free-operant as opposed to a discrete-

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training trials format; thus, one purpose of this study was to contrast the two. Second, if a free-operant procedure is effective in bringing about the desired change, can the response be brought under discriminative stimulus (S^D) control? Certainly, the argument that BP can be conditioned as a free operant would be strengthened by a demonstration that acquired increases and decreases in it can be brought under S^D control. Third, as Blanchard and Young (1974) noted, there is a possibility that some of the previously assembled data may be contaminated by instructional set. It has been reported (Beatty, 1972; Lynch and Paskewitz, 1971; Walsh, 1974) that instructional set has a significant effect on self-control of alpha; perhaps it may influence blood pressure in much the same way. A fourth task is to determine if a subject who has learned to raise and/or lower BP with the initial aid of an exteroceptive feedback signal can maintain that control after the external signal has been withdrawn. Finally, a control group is included in the study.

METHOD

Subjects

Twenty-four normotensive volunteer college students at the University of New Orleans served; four were assigned randomly to each of six groups. There were 12 males and 12 females aged between 19 and 33 yr with a mean age of 24. The mean diastolic BP was 72.90 with $SD = 5.57$.

Apparatus

A full description of the instrumentation is available elsewhere (Elder *et al.*, 1977). Essentially, it consisted of a custom-made tracking device coupled to a strip chart recorder (Speedo-max, Type G), an oscilloscope, two standardized inflatable cuffs (Narco Bio-Systems 712-0016), a 12.5-cm, 8-ohm, wall-mounted speaker, and air supply. One cuff was placed on each arm of the subject, taking care to position the microphone imbedded in the distal margin of it

directly over the brachial artery. In the free-operant (FO) training mode, a relatively continuous record of BP was secured by alternately inflating the two cuffs for periods of 100 sec each, and tracking the moment-to-moment fluctuations in diastolic BP by readjusting cuff pressure every three to four heartbeats. Tracking BP was accomplished by detecting K sounds and manipulating pressure in the cuff throughout each 100-sec inflation interval (run) in order to hold K-sound intensities constant.

Although systolic blood pressure can also be measured, diastolic BP was selected as the dependent measure because medically it is considered more important than systolic BP, and the data of Elder, Leftwich, and Wilkerson (1974) indicate that subjects can learn to control their BP more rapidly if they are trained with diastolic-contingent rather than systolic-contingent feedback/reinforcement.

In the FO mode, auditory feedback was available throughout each 100-sec cuff-inflation cycle. The feedback took the form of changes in the pitch of an audible tone proportional to changes in cuff pressure. A single BP score was obtained from each run by selecting the level at which the tracking instrument began to track the threshold pressure, and was designated as the score for that run.

The apparatus was housed in an air-conditioned, sound-attenuated room 2.26 by 4.09 m. The subject sat in an upholstered reclining chair facing a blank white wall and away from the experimenter and apparatus. The experimenter remained in the room behind and to one side of the subject in order to maintain constant and close surveillance of the apparatus and subject.

Design

To satisfy the fourfold purpose of this study, a 2 by 3 design was used in which two conditioning formats (free operant and discrete trials) were factorially compared with three strategies: instrumental conditioning (IC), instructional set (IS), and control (C).

Thus, there were six groups. The first was the instrumental conditioning-free operant (IC-FO), in which the diastolic BP threshold was tracked throughout each run and proportional auditory feedback was available whenever tracking occurred. The second was the instrumental conditioning-discrete trials (IC-DT) group, and in this case BP was tracked only during the initial and final 10 sec of each run; feedback/reinforcement was available only at those times. Both were considered experimental groups and were similar in every respect, except that BP was tracked on a continuous basis in the first; in the latter, cuff pressure was held constant at the diastolic threshold without auditory feedback, except for the initial and final 10 sec of each run. The third and fourth groups were treated in a manner identical to Groups 1 and 2, except for the fact that subjects were provided with detailed instructions regarding their role in the experiment and feedback/reinforcement was never present. In like manner, the fifth group—control-free operant (C-FO)—had their BP measured on a continuous basis and the sixth group—control-discrete trials, (C-DT)—had their BP measured for the first and last 10 sec of each run. Unlike the IC and IS groups, they received neither feedback nor detailed instruction, but were simply advised to relax and breathe normally.

Subjects were assigned to groups randomly, and exposure to assigned procedures was repeated until they exhibited an increase and decrease in BP of 10% to 15% for two consecutive training sessions, or until they had completed a total of 10 successive training sessions. Each session consisted of 20, 100-sec runs, with an interrun interval of 20 to 50 sec.

In the first session, basal BP was determined. Each succeeding session was divided into two parts, during which training was aimed toward increases (UP responses) or decreases (DOWN responses). High (H) and low (L) levels of room illumination were paired with UP and DOWN training periods in a counterbalanced order over the first and second halves of each session, across subjects, and over days to see if acquired UP

and DOWN BP responses could be brought under S^D control.

Room illumination generated with recessed incandescent ceiling lights was used as the S^D . To distinguish the basal from training and test sessions, a moderate (M) level (120cd/m^2) of illumination was used; the H and L levels were set at 400cd/m^2 and 8.5cd/m^2 , respectively. S^D intensities were determined with a Textronix J16 Digital Photometer and a J6 503 probe. The instrument was normalized to human eye sensitivity and all measurements were made from seated eye level of the subject.

Procedure

Before each session, subjects were sent to a nearby restroom to urinate. Then, they were asked to report any use of medication (except oral contraceptives) or alcohol within the previous 24 hr. Whenever an affirmative reply was received, the session was rescheduled; if not, the experimenter and subject proceeded with the experiment.

On the first day, basal BP determinations were made, and the procedure consisted of setting room illumination at the M level, obtaining the subject's informed consent, and then asking the subject to be seated. Next, the following instructions were given: "Today we are going to measure your blood pressure. To do so, we must place a cuff on each arm. The procedure calls for you to sit back, breathe normally, and move as little as possible while we alternately inflate first one cuff and then the other. The entire sequence will take about one hour." After a cuff was placed on each arm, the subject was allowed to sit back in the chair and accommodate to the laboratory setting for about 15 min. Twenty successive runs followed immediately. The subject was then dismissed and asked to return the next day at approximately the same hour.

The acquisition phase began on Day 2. Subjects in the IC-FO and IC-DT groups were told simply to listen for a tone and try to make it go (up/down). Then, room illumination was

changed from M to either the H or L level and part 1 of the training session was initiated. After 10 runs were completed, the experimenter said; "Now your task is to make your blood pressure go (up/down). Do the best you can." And room illumination was adjusted to the prescribed setting.

All IC subjects received four blank runs (runs without auditory feedback) per acquisition session to assess the role of feedback in these two IC groups. Two were interspersed randomly among the 10 UP responses, and two were administered during the DOWN response period. The only constraint on random assignment of blank runs during a given period (UP or DOWN) of a session was that one was always presented during a left-cuff inflation cycle and the other when the right cuff was activated.

Subjects in the IS-FO and IS-DT condition were told: "The purpose of this experiment is to see if you can learn to control your blood pressure. When room illumination is (bright/dim, as the case may be) you are to try and (raise/lower) your pressure; when the room illumination is (bright/dim) you are to (lower/raise) your pressure. Please sit back in the chair, breathe normally, try not to move your arms and do the best you can." After 10 trials, the instructions were repeated for emphasis.

The instructions to subjects in the control groups (C-FO and C-DT) were: "The purpose of this experiment is to measure your blood pressure. Please sit back in the chair, breathe normally, try not to move your arms, and when room illumination is (bright/dim) relax as much as you like." In the C condition, the intent was to establish a typical relaxed state, rather than deep muscular relaxation of the type engendered by progressive relaxation. None of the instructions was repeated after the first day of training.

Soon after instructions were given, training began. Room illumination was set at the previously determined level and the subject was exposed to 10 successive runs in which cuff in-

flation alternated left-right; this constituted the first half of the session. On completion of this series, room illumination was changed to the opposite level and training was resumed for 10 more successive runs. When the second half was completed, the subject was excused and asked to return the next day.

In the event that subjects in the instrumental conditioning groups succeeded in acquiring UP and DOWN BP responses with the aid of exteroceptive feedback, it became necessary to determine their ability to maintain the new responses when the external feedback was withdrawn. To determine how well each subject could perform the newly acquired response without the aid of external feedback/reinforcement, two successive daily test sessions were carried out at the end of the acquisition phase. Test sessions were similar to training sessions, except that the auditory feedback signal was discontinued and the cuff-inflation cycle was shortened to 10 sec every 2 min to remove as many sources of feedback as possible. Reducing run length from 100 to 10 sec eliminated the possibility that subjects may have learned to rely on slight moment-to-moment adjustments in cuff pressure as a cue; increasing the interval between runs from a 20- to 50-sec range to 2-min interval gave the subjects an opportunity to perform other possibly competing responses. A free interval during which other behaviors could occur, such as relaxing, was necessary to test the controlling properties of the respective S^D's on BP responses. The longer interrun interval during the test phase assured that the subjects would have to maintain their newly acquired responses for as long a time as was required during acquisition.

Followup

All subjects were asked to return in three weeks for a followup determination. Since they were unpaid volunteers, direct contact was required to schedule followup sessions. The procedure was identical to that used during the test sessions.

RESULTS

Each subject's mean basal BP level was determined by averaging across all 20 scores obtained during Session 1. As a check against the possibility of pretreatment differences between the six groups, these mean values were subjected to a 2 by 3 analysis of variance, which failed to disclose any statistically significant differences. In consideration of the possibility that BP levels may not have stabilized by the end of the first session, a second 2 by 3 analysis of variance was performed on only BP measurements taken over the last six runs of the first session; again, no differences were found between the groups or between runs.

Because the training criteria had been expressed at the outset as a 10% to 15% change in response with respect to basal BP, the scores obtained over the training, test, and followup

sessions were converted to and analyzed as percentages of basal pressure. Such a procedure had the additional advantage of adjusting basal BP to a common origin for all subjects, even though significant pretreatment differences failed to emerge from analysis of the raw basal BP scores. However, to give some indication of the mean raw-score BP values at some points in the study, individual subject's BP scores obtained on the last day of training, the last of the two test days, and at the followup session have been listed in Table 1. Since there was no obvious advantage in making the direct within-subject comparison of the direction of behavior change (UP *versus* DOWN), the data analyses were simplified by analyzing UP and DOWN responses separately.

Training

Tabulation of the number of training sessions required by each group to reach the 10% to

Table 1
Summary of Trials to Criterion and Raw BP Scores at Various Stages of the Experiment

Group	Subject	Number of Sessions to Complete Criterion	Last Training Session (U = up, D = down)	Last Test Day	Followup
IC-FO	1	7	93.2 U; 68.9 D	91.5; 69.0	NA*
	2	5	79.1 U; 60.0 D	82.3; 62.9	82.6; 62.3
	3	5	87.0 U; 68.6 D	87.6; 66.2	88.3; 65.7
	4	6	83.2 U; 63.4 D	84.9; 62.1	86.0; 62.2
IC-DT	1	10†	77.7 U; 66.1 D	74.6; 66.0	72.0; 70.5
	2	10	75.4 U; 73.4 D	78.8; 74.9	NA
	3	10	77.0 U; 72.6 D	76.7; 72.8	NA
	4	10	68.9 U; 65.0 D	66.1; 65.3	NA
IS-FO	1	10	75.0 U; 69.0 D	75.8; 71.2	73.9; 72.2
	2	10	70.2 U; 62.4 D	69.1; 65.3	66.4; 67.5
	3	10	67.2 U; 66.1 D	68.4; 69.0	68.4; 69.2
	4	10	70.4 U; 65.8 D	69.9; 65.7	69.3; 68.9
IS-DT	1	10	66.6 U; 68.6 D	66.5; 65.5	66.3; 67.6
	2	10	76.3 U; 72.0 D	72.7; 73.7	72.4; 74.6
	3	10	79.2 U; 73.4 D	75.8; 74.8	75.1; 74.0
	4	10	63.9 U; 65.2 D	63.3; 63.3	NA
R-FO	1	10	69.5 U; 72.8 D	68.0; 69.5	NA
	2	10	75.9 U; 76.1 D	81.3; 79.1	76.9; 78.6
	3	10	60.8 U; 65.4 D	63.3; 63.5	NA
	4	10	67.5 U; 68.5 D	66.8; 68.5	NA
R-DT	1	10	71.3 U; 71.4 D	67.0; 67.3	72.1; 70.3
	2	10	76.6 U; 75.6 D	77.0; 74.7	NA
	3	10	63.7 U; 62.7 D	67.8; 67.4	NA
	4	10	67.3 U; 69.1 D	77.5; 75.9	75.0; 75.5

*NA = not available.

†Subject did not attain criterion within 10 sessions.

15% performance criterion (see Table 1) revealed that two subjects in the IC-FO group required five sessions, one required six, and the other required seven, for a mean of 5.75 sessions, to reach criterion; each of these values includes the two criterion sessions. None of the subjects in the other five groups was able to satisfy this criterion within the 10 available training sessions. Therefore, in terms of sessions to criterion, the IC-FO condition proved to be superior to the other five.

Analysis of the UP BP response scores yielded a significant effect due to format ($F(2,18) = 5.86$, $p < 0.01$), training strategy ($F(2,18) = 5.86$, $p < 0.01$), sessions ($F(4,119) = 4.81$, $p < 0.001$), and training strategy by sessions ($F(4,119) = 4.15$, $p < 0.0004$). As can be seen by inspection of the center field of Figure 1, these effects can be accounted for by the superior performance of the IC-FO group. Since training was discontinued after the subjects in this condition reached criterion, a full set of performance data was available only for Sessions 1 to 5. The mean performance of the two subjects

in the IC-FO condition who required six and seven sessions to reach criterion has been displayed in Figure 1, but their scores were not included in the statistical analysis.

Analysis of the DOWN scores yielded reliable effects due to training strategy ($F(2,2) = 5.09$, $p < 0.02$), sessions ($F(4,119) = 4.65$, $p < 0.002$), format $\times$ sessions ($F(4,119) = 2.15$, $p < 0.04$), and a training strategy by sessions interaction ($F(4,119) = 2.15$, $p < 0.04$). These differences have been illustrated in the center field of Figure 2. As was the case with the UP data, only measurements taken during the training Sessions 1 to 5 were included in the analysis, but the data collected over Sessions 6 to 10 have been displayed in the figure for visual comparison. In general, the data in Figures 1 and 2 show that subjects in the IC-FO condition learned to changed their BP UP and DOWN as much as 13% of basal BP in five to seven sessions; subjects in the other five groups showed little or no change.

To consider to what degree the mean UP and DOWN scores generated by the IC-FO group

Fig. 1. Plot of group mean diastolic blood pressure expressed as per cent of basal over training sessions, test sessions, and followup. These data include the UP response phase only.

Fig. 2. Plot of group mean diastolic blood pressure expressed as per cent of basal over training sessions, test sessions, and followup. These data include the DOWN response phase only.

Fig. 3. Comparison of individual subjects' mean diastolic blood pressure expressed as per cent of basal over training sessions, test sessions, and followup for the IC-FO condition only. Both UP and DOWN responses are included.

characterized the performance of the group as a whole, individual subject's BP responses were determined, and these have been plotted in Figure 3. Inspection of the left-hand field of the Figure reveals that all four subjects in the group exhibited strikingly similar behavior. Therefore, the mean UP scores shown in Figure 1 and the mean DOWN scores shown in Figure 2 reflect the performance of the group fairly accurately.

Test Sessions

When the UP scores were analyzed, three effects emerged: format ($F(1,18) = 16.81, p < 0.006$), training strategies ($F(2,18) = 22.08, p < 0.0001$), and the format by training strategy interaction ($F(2,18) = 27.35, p < 0.0001$). The differences represented by these comparisons have been summarized in the right-hand portion of Figure 1.

A similar analysis of the DOWN scores revealed significant effects due to format ($F(1,18) = 21.71, p < 0.0002$), training strategies ($F(2,18) = 25.28, p < 0.0001$), and format by sessions ($F(1,47) = 8.30, p < 0.01$). These dif-

ferences have been displayed in Figure 2. Here, too, the superiority of the IC-FO group is clear, as is borne out by the individual subject's performance curves shown in Figure 3.

Since the purpose of the test sessions was to determine whether or not subjects who had learned bidirectional BP control with the aid of an auditory feedback signal could retain their new skill when feedback was withdrawn, consideration of their performance on blank runs administered during acquisition, as well as their performance over posttraining test sessions, is appropriate at this point. The pertinent data have been displayed in Figure 4. Note that performance of the subjects in the IC-FO group was very similar on blank runs as well as the runs during which feedback was present. The right-hand panel of Figure 4 shows that the IC-DT group failed to show systematic changes in BP on either the blank or feedback runs.

Followup

Only 14 of the original 24 subjects were available for observation three weeks after the test

Fig. 4. Comparison of group mean diastolic blood-pressure performance during runs when auditory feedback/reinforcement was available with performance during blank runs when feedback/reinforcement was not present.

sessions, thus rendering the followup data incomplete. Even so, UP and DOWN performance means were tabulated from the available data, and they have been plotted in the right-hand margins of Figures 1 and 2, respectively. Because of the paucity of followup data, statistical analyses were not performed, but simple inspection of these data suggests that the subjects who returned for followup were able to produce UP and DOWN BP responses equal in magnitude to those observed during the later stages of training and over test sessions.

DISCUSSION

The major aim of this study was to examine the possibility that BP could be observed and modified as a free operant, and the data generated by it indicate that it can. More specifically, it was demonstrated that acquisition of bidirectional BP control within subjects occurred more rapidly with a free-operant training format than with a discrete-trials procedure. In addition, it was observed that bidirectional BP behavior could be brought under S^D control, and that this control was maintained after the external feedback signal had been withdrawn. Retention tests carried out three weeks later were incomplete because some of the subjects were no longer available, but the evidence collected indicated that the acquired bidirectional response had not been lost.

Although these data support the general view that autonomically mediated responses are acquired and lost in accordance with the laws of instrumental (operant) conditioning, several aspects of the present study must be borne in mind when drawing such an inference. For example, it should be pointed out that auditory feedback and IS were confounded in the case of the instrumental conditioning groups (IC-FO and IC-DT), since it was necessary to give a minimum set of instructions to the subjects in this condition. Therefore, the superior performance of the IC-FO group may reflect the interactive affects of continuous, proportional feed-

back/reinforcement with IS. While there can be little doubt that IS is an influential psychological variable in many types of situations, and may influence the outcomes of studies done with human subjects, there was no evidence that it had a main effect here; but it may have interacted with the procedure.

Second, it is important to note that the observed advantage of the FO over the DT mode may be accounted for by the fact that subjects in the former simply received more feedback than those in the latter. Additional studies are needed to clarify the role of various amounts of feedback, but the present purpose was to see how the older procedure of measuring BP at discrete points compared with the more recently developed method of Elder *et al.*, and the data are in favor of the FO method. To what extent that advantage can be attributed to more or less feedback, massed *versus* spaced training, *etc.* remains to be determined.

Third, in studies of this type there is always the question of what the subjects had to say about their experience after the study was over. Some subjects reported that they did not know what was going on, and others described their analysis of the situation in detail. Some of these verbal reports were unreliable. For example, one subject in this experiment described a rather elaborate cognitive strategy that he exercised to control BP; but, the fact of the matter was that he had been assigned to the control group and had failed to demonstrate any blood pressure changes. Thus, the accuracy of subjects' reports of experimental contingencies and consequences was questionable.

With respect to the possible problem of skeletal muscle or respiratory response mediation of the observed BP responses, it may be helpful to note that an observer was present at all times. Since subjects were required to produce an UP and a DOWN response in the same session, any attempt to perform the correct response by altering breathing or tensing and/or relaxing musculature would have been easier to identify than had they been required to change BP in one di-

rection only. In no case throughout this experiment was it apparent that the subject was using breathing or muscle tension to bring about the observed bidirectional changes in BP.

In summary, the data support the contention that visceral responses are subject to the laws of instrumental conditioning in much the same way that skeletal responses are. However, before conditioned cardiovascular behavior is well understood or clinical applications are fully justified, it will be necessary to determine to what extent acquired BP behavior generalizes beyond the laboratory, and to what degree acquired control of BP can be decoupled from muscular tension, how sensitive the newly learned response is to instrumental extinction, and even whether hypertensive BP behavior is acquired and lost in a fashion similar to acquisition and extinction of normotensive BP responses. These and many more questions have to be answered before the clinical utility of the procedure can be adequately appraised. Nevertheless, these data constitute additional evidence that human subjects can be trained to control their own blood pressure.

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Received 11 June 1976.

(Final acceptance 5 October 1976.)