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Body Temperature Influence on Time Perception

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ABSTRACT. The chemical clock hypothesis implies a causal link between body temperature and the perception of duration. A strict interpretation of this construct requires a common slope value in an Arrhenius plot that relates time to temperature for every individual tested. Previous studies testing this proposition have confirmed a general relationship for data summed across multiple subjects. However, the same studies raise doubts as to whether this relationship holds for each and every individual tested. Unfortunately, these investigations have been limited by methodological constraints, thus, one could argue that the strong isomorphism intrinsic to the chemical clock hypothesis has yet to be fairly tested. In the present experiment, I sought to distinguish the effects of selective head temperature changes on the estimation of duration. Nonlinear decreases in estimated duration were observed with ascending deep auditory canal temperature. These findings support the contention of a thermally stable region of temporal perception bounded by conditions in which temporal estimates directly depend on body temperature. In contradicting physiological adequacy as an explanatory construct, the present results suggest a direct relationship between time perception and the homeothermic platform. I compare these results with earlier findings concerning the chemical clock concept and examine respective discrepancies as a basis for a fuller understanding of a temporal phenomenon that is frequently referred to as the internal clock.

TIMING AND TEMPORAL DISCRIMINATION are central to the synchronization of perception and action. As a fundamental property in the coordination of purposeful activity, the ability to accurately estimate duration is a key characteristic of skillful performance. Although much of the information required for duration estimation resides in changes intrinsic to the environmental display, the source and effect of endogenous information that contributes to a sense of time is the subject of continuing contention. The original search for endogenous influences on time perception centered on global physiological processes such as heart rate and respiration (see Munsterberg in Nichols, 1890; Schaefer & Gilliland, 1938) which proved, disappointingly, to have little or no discernible relationship. Similar frustrations have met attempts to link more sensitive measures of central nervous system activity such as EEG alpha rhythm (Anliker, 1963; Dureman & Edstrom, 1964; Surwillo, 1966; Treisman, 1984; Werboff, 1962). The one exception to this spectrum of negative findings has been the demonstrable and consistent effect of body temperature.

The general notion of a temperature influence on time perception may be traced to Pieron (1923, 1945)[1] who suggested that "if the speed of organic processes are modified, by variation and temperature for instance, mental time will increase or decrease proportionally." It was Pieron's student Francois (1927 a, b), however, who conducted the original empirical evaluations of the proposition. Yet, it is Hoagland who is associated most frequently with this general effect, mainly because of his postulate of a chemical clock to control estimates of duration. Using both his own data and those previously collected by Francois, Hoagland (1933) proposed that estimates of duration were directly dependent on internal body temperature. He described this relationship through the Van't Hoff-Arrhenius equation, which describes the speed of a chemical reaction in relationship to its temperature in degrees Kelvin. In observing that the collective data provided a unitary slope value within this equation, Hoagland (1933) concluded that our judgments of time depend upon "an underlying chemical master reaction, implying an irreversible chemical mechanism controlling the consciousness of duration."

There have been a number of experimental investigations of the fundamental isomorphism explicit in Hoagland's statement. Many of them support a general temperature dependency that holds for the mean trends across a number of experimental participants. However, many of the same studies point to the clear violation by a number of individuals of the speeding effect that should occur with increased body temperature. These violations represent only one objection to Hoagland's assertion. However, the majority of studies testing his proposition are

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[1] I have here attributed the earliest linkage between perceived time and body temperature to the work of Pieron. However, it is facile to deny the influence of Bergson, Guyau, and earlier German theorists such as Mach and Munsterberg in this development. Nor can the work of James be excluded from the pattern of thought that led to Pieron's statement. Hence, although I believe the attribution to be correct, the foundation of these earlier researchers cannot go without acknowledgment. For the student of the area, it is of course interesting to compare this with the historical antecedents of the linkage between time and temperature in the physical realm as mediated through the second law of thermodynamics, of which the present topic is arguably a subset.

themselves flawed. Objections to previous studies include the use of remote and often unrepresentative sites to monitor change in temperature of the cortex, the use of febrile subjects when the source of the pyrogenic effect is not established, and the interpolation of other performance tasks in the period to be estimated, a manipulation known to affect perceived duration (cf. Axel, 1924). Each of these objections is less serious than one confounding effect that permeates almost all studies in this area: stress.

Experiments testing the relationship between time perception and temperature typically expose subjects to a level of stress they are constantly aware of, sometimes painfully so. Stressors have ranged from exposure to hazardous ambient thermal conditions to local heating caused by the use of electrical administration. The confound is that stress itself has been shown to exert a strong influence on time perception (e.g., Langer, Wapner, & Werner, 1958). Hence, previous efforts have been unable to distinguish among the concurrent influences of stress and temperature variation. Also, the specific prediction of a temperature influence by Hoagland concerns change in the temperature of the central nervous system, particularly the cortical level. Not only did researchers in previous studies use measurements from remote sites (e.g., rectal temperature) but they also failed to control for the most sensitive thermoregulatory adjustments of the brain in which specific structures and processes (e.g., countercurrent heat exchange) act to regulate against such global effects as total body heating. Therefore, I designed the present experiment to test the predictions central to Hoagland's postulate without the concomitant effects of stress. Further, I used a procedure that permitted a selective change in head temperature, as measured in the deep auditory meatus, without the subject being able to distinguish such an elevation. This allowed for the administration of a placebo condition in which the effect of equipment use alone could be evaluated and for a veridical test of the time/temperature relationship as originally posited to be performed.

Method

Subjects

Twelve men who were members of either the faculty, staff, or student body of the University of Illinois served as subjects. They were not paid for their participation. They were aged 26.6 ± 10.4 years, with a height of 179.5 ± 21.2 cm and weight of 175.6 ± 69.4 lb. (mean ± range). Each of the subjects was in professed good health at the time of the testing.

Task and Procedure

The summaries that have been presented concerning the methods used in time estimation (e.g., Bindra & Waksberg, 1956; Clausen, 1950; Wallace & Rabin, 1960), suggest that interval production is the most effective method for assessing the perception of duration. Accordingly, subjects were required to estimate three durations; 1s, 11s, and 41s, respectively. The subjects produced unfilled time periods by the depression and release of one microswitch to indicate the start of the period, and the depression and release of an adjacent microswitch to indicate the termination of the period. All subjects used their right hands to control the time estimates, whereas the left hand was used to record trials on a pegboard. All subjects were asked to count quietly to themselves during the estimated interval; this request was made, in part, to preempt subjects' discovery of a counting strategy at some unknown point in the experiment (Doob, 1971). To produce filled intervals, subjects depressed a telegraph key throughout the whole estimated interval. Consequently, the filling activity was motoric and muscular in nature. Both filled and unfilled intervals were recorded from electric clock timers accurate to one ms.

Some controversy has surrounded the problem of time estimation methods through either filled or unfilled manipulations (e.g., Axel, 1924; Hogan, 1978). Two contrasting views contend that the experience of duration is either linearly and positively related to stimulus complexity (Ornstein, 1969), or that it is linearly but negatively related to the complexity of the stimulus that fills an interval (Priestley, 1968). In view of this conflict, both filled- and unfilled-time procedures were employed in the present experiment. To obviate the possibility that attention was directed toward distracting visual and auditory stimuli, which have previously been shown to affect estimation (Gilliland, Hofeld, & Eckstrand, 1946), I conducted the experiments in a room that was sound and light isolated. In addition, to further reduce the availability of temporal cues to the subject, all contact between participant and experimenter ceased for the duration of each test session. Timepieces were removed prior to entry into the experimental environment.

Temperature Manipulation and Measurement

Change in head temperature was induced by a heating helmet that provided radiant heating from an electrical source applied along the saggital plane from frontal to occipital lobes (Hancock, 1983). A thermal sensor located in the helmet lining measured the level of heat and provided a feedback loop via a thermostat for both monitoring and controlling helmet temperature. The monitoring device for the temperature of the helmet was a thermistor, connected to a temperature display. The electrical heating was achieved via a temperature controller. The subject was isolated from the temperature control equipment by a rubber insulating cap. Over the internal insulating cap the flexible temperature-induction helmet was affixed and secured using insulating tape.

Changes in head temperature were measured at the site of the deep auditory meatus. The relatively close proximity of the tympanic site to the hypothalamic area and cortex in general has indicated to some workers that this site provides the most representative change in the temperature of the cortical cavity itself

(Benzinger, 1969). The sensor was placed adjacent to the actual membrane and away from any potentially painful contact. Included in the design of the sensor was an insulating cotton wool insert, to minimize thermal artifacts from the pinna. In addition to changes in auditory meatus temperature, head skin and initial and final oral and immediate ambient temperatures were taken. The control condition consisted of an insulating cap with no temperature helmet. The placebo condition consisted of both cap and helmet but with no external heating applied. In the heat conditions, temperature measured in the deep auditory meatus was elevated by 0.75°C and 1.50°C before the start of the experiment.

Procedure

Subjects were requested to attend five consecutive and procedurally equivalent experimental sessions that lasted approximately 1 hr each. Subjects were tested at the same time of day for 5 consecutive days. This manipulation was used to mitigate any possible effects of a diurnal variation in time estimation, as has been suggested by previous research (Pfaff, 1968; Thor, 1962; but see also Hancock, Vercruyssen, & Rodenburg, 1992). The only difference among experimental sessions was in the thermal condition. For each subject the first experimental session was a practice period in the same conditions as those described as control. Often, subjects require a certain period to become familiar with the equipment and experimental surroundings. As a consequence, data from each initial practice period was recorded but not used in the reported analysis. The order of administration of heating conditions was randomized across subjects.

Experimental Design

The scores for the 12 participating subjects were analyzed using a fixed-effects balanced analysis of variance. There were four within-subject factors: estimation type, estimation length, thermal condition, and trial for three durations: 1 s, 11 s, and 41 s. The two types of estimation were filled- and unfilled-time procedures. The thermal condition consisted of four levels: control (no helmet, no heat), Placebo (helmet, no heat), Heat 1 (helmet, mild heat = 0.75°C elevation), and Heat 2 (helmet, more severe heating = 1.50°C elevation). There were 20 trials per period per estimation type per condition. Each subject produced 480 responses, for a total of 5,760 trials analyzed. Each temporal estimation was converted to a ratio of the estimated interval divided by the target interval, and these data were used in analysis.

Results

Mean Ratio of Temporal Estimates

Because preliminary analysis indicated only marginal effects for the trial factor in the present experimental findings, the present analysis summed over trials. Each estimate was converted to a ratio score of the estimate versus the target interval, and these values were summed across the 20 trials per condition to represent the subject's stable performance in that condition. Summed across trials, there were no significant interactions between estimation type, ratio of estimated to actual interval, or thermal condition. Also, there was no main effect for interval. The latter observation suggests a degree of homogeneity in the mechanism responsible for estimates of differing length. For the factor estimation type, the filled manipulation produced marginally shorter responses than those produced in the unfilled condition, $F(1, 11) = 4.07, p = .069$. The mean absolute values were 18.91 s and 19.49 s for the filled and unfilled type, summed across all intervals. Of central concern was a significant main effect for the thermal condition, $F(3, 33) = 4.205$, $p \leq .015$. The Newman-Keuls post hoc procedure distinguished estimates under the Heat 2 condition as significantly shorter ($p < .05$) than estimates under all other thermal conditions, the estimates of which did not differ significantly from each other. The data for the absolute estimate values for each interval and the body temperature values in each condition are given in Table 1.

Total Time of Exposure

Subjects were asked to estimate the total time of each exposure after every experimental testing session. (The end of each session was signaled by the entry of the experimenter into the performance room.) Both estimated time and elapsed time were recorded and used in analysis. This analysis indicated no significant differences for the factor-elapsed versus estimated time or for the factor thermal condition (Fs < 1). The mean estimated time was 49.2 min; the mean elapsed time was 49.6 min.

Individual Data

The data for the individual subjects are presented in Figure 1 (Subjects 1–6) and Figure 2 (Subjects 7–12). As is apparent in both figures, the pattern of results was similar for all individuals. The most striking result was the reduction in estimation for each subject under the most severe heating condition. For the control, placebo, and mild heating conditions, the individual patterns were slightly less systematic. The overall pattern is represented by a small, progressive increase in estimation across the control, placebo, and mild heat conditions, followed by a significant reduction in estimates in the severe heat condition. Two subjects, one from each group of six, appear to have had a sensitivity to the mild heat condition such that the downward trend in estimation appears at a lower level of elevation (see Figures 1 and 2). All other subjects began such a trend toward underestimation as temperature was elevated from the mild to more severe heat condition. This may indicate some individual difference with respect to sensitivity to absolute temperature change.

TABLE 1
Means and Standard Deviations for the Three Estimated Periods and Two Temperature Measures, Experiment 1.

Measure/Condition	Control	Placebo	Heat 1	Heat 2
Period 1 (1 sec)				
M(s)	1.006	1.056	1.063	0.981
SD(s)	0.313	0.283	0.310	0.258
Period 2 (11 sec)				
M(s)	12.021	12.115	12.689	11.038
SD(s)	2.859	2.576	3.573	3.083
Period 3 (41 sec)				
M(s)	45.032	46.038	47.256	40.044
SD(s)	10.766	10.936	12.142	10.493
Tympanic temperature				
M(°C)	36.5	36.7	37.1	37.4
Change T(°C)	+0.1	+0.3	+0.8	+1.1
Skin temperature				
M(°C)	34.4	35.8	37.3	37.9
Change T(°C)	0.0	+1.4	+2.8	+3.4

The observation that each individual's pattern remains consistent is in contrast to Bell's (1966) results. Disparity could be attributed to the differential heating manipulation. Consistency was observed even though each subject experienced a different order of administration of experimental conditions. This consistency argues against the possibility of an asymmetric transfer of unwanted strategy by the subject in the present work (Poulton, 1973).

Thermal Data

The data for the temperature values are of a descriptive nature and were collected periodically during each exposure. Upon entering the experimental room, subjects had two temperature sensors attached to monitor deep auditory meatus and head skin temperature. Subjects' stable baseline temperatures were recorded for each measure before any experimental manipulation. Subsequent measures were taken at 3-min intervals throughout each experimental session, with the first trial and first recording being coincident. The actual length of each session, and hence the number of recordings, varied with both session and subject. To standardize recordings, a measure was reported for each decile of the total exposure, and it is on these values that subsequent descriptive data are based.

In the control condition, mean deep auditory meatus (canal) temperature was 36.4°C and exhibited a change of +0.1°C from the mean baseline value. In the

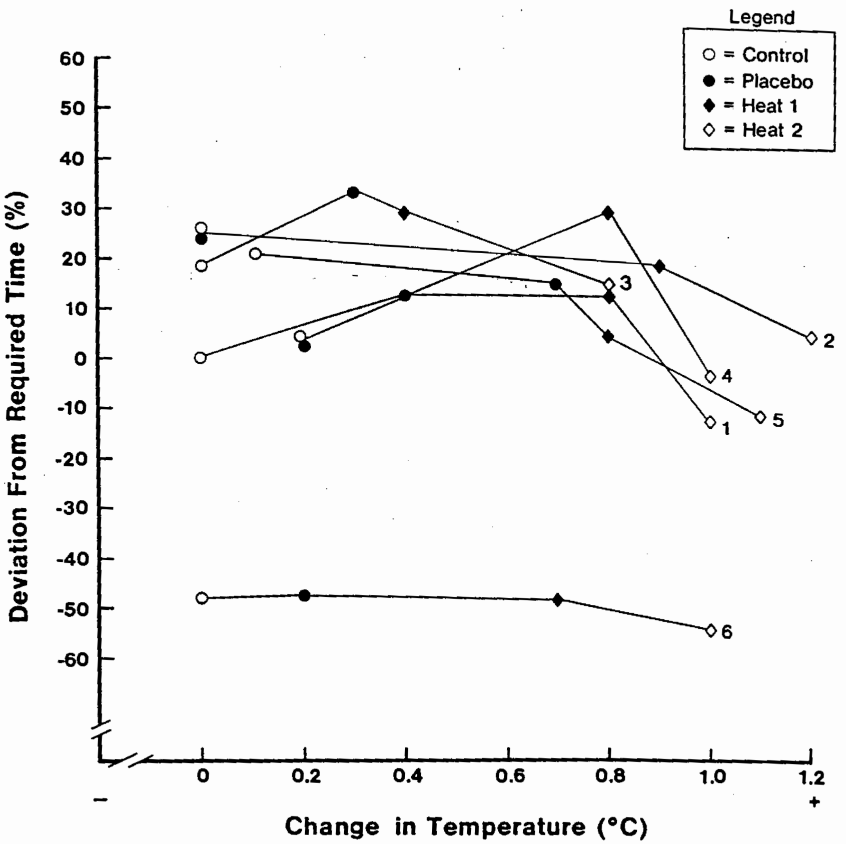

FIGURE 1. Individual deviations in production values (Subjects 1–6) as a function of changes in temperature in the control, placebo, and heated conditions.

placebo condition, the mean canal temperature was 36.7°C, a +0.3°C increase over mean baseline temperature. The equivalent mean values for Heat 1 and Heat 2 were 37.1°C and 37.4°C, respectively. These were mean rises of +0.8°C and +1.1°C over baseline values in each condition. The equivalent values for skin temperature were: control = 34.4°C, placebo = 35.8°C, Heat 1 = 37.3°C, and Heat 2 = 37.9°C. These represented mean rises of 0.0, 1.4, 2.8, and 3.4°C, respectively over baseline measures. These data are presented in Table 1. The results are systematic and suggest that whereas time estimation appeared to be relatively unmoved by mild temperature perturbations, there was some consistent response from all subjects to some larger increase in temperature of the head.

Discussion

Behavioral Analysis

At the level of behavioral analysis the results support an arousal interpretation. The strongest advocate of this construct is Poulton (1976, 1977), who indicated that performance under a variety of environmental stressors may be facilitated through the action of the stress in eliciting behavioral arousal. Despite Broadbent's (1963) observation that heat may operate through a fundamentally different mediational process than, for example, noise or vibration, Poulton has continued to propose an arousal account of performance under thermal stress.

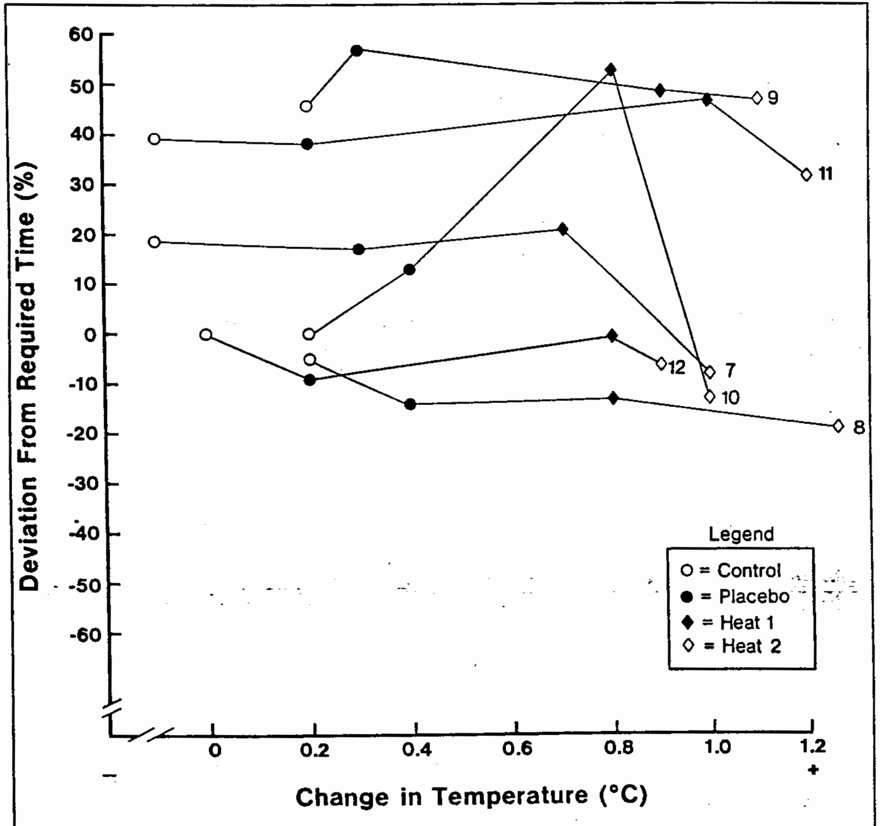

FIGURE 2. Individual deviations in production values (Subjects 7–12) as a function of changes in temperature in the control, placebo, and heated conditions.

Poulton proposed four stages of response to heat: (a) Immediate entry into a heated environment is arousing and consequently improves performance (Poulton & Kerslake, 1965); (b) mild heat induces lassitude and a consequent depression in behavioral arousal, diminishing performance capability (Mackworth, 1950); (c) progressive increase in heat elevates behavioral arousal and facilitates performance (Pepler, 1958); and (d) excessive heat is debilitating and exhaustive, and eventually reaches the stage of a rapid decline in task efficiency (Hancock, 1981, 1982). Certain phases appear analogous to the triphasic response in the general adaptation syndrome of Selye (1956).

The elements in Poulton's account appear to accommodate the present results. For example, although the sequential rises in mean estimation across the control, placebo, and mild heat conditions were not significant, the measure of dispersion was significantly greater in the mild heat condition than in any other condition. Consequently, it may be argued that the mild heat constitutes the lassitude phase when arousal is depressed and time estimation is more variable. The subsequent decrease in estimated time is analogous to the stages of elevated arousal with more severe heat. The stage of exhaustion does not appear in the current data because a relatively small volume of the body was heated, and the body may eventually act successfully to regulate against the local temperature change. It is important to note that this account for behavioral arousal is based on the effect of the temperature change itself and not on the method of manipulation, which in the present experiment was constituted by helmet administration.

A priori, the latter assumption appears reasonable as the effect of helmet administration has been observed to be ineffective in changing capability on a variety of performance tasks (Hancock, 1983; Hancock & Dirkin, 1982; Holt & Brainard, 1976). Thus the time course of performance capability in heat under the mediation of behavioral arousal appears able to encapsulate the results from this experiment. However, there are certain incongruities, in addition to more fundamental objections. One problem is that the threshold between the effect of lassitude and subsequent arousal occurred in the range of ambient temperature at which the body exhibits a noncompensable increase. This threshold has been important in identifying performance limits (Grether, 1973; Hancock, 1981). However, the present low-heat condition caused a rise in head temperature and the possible disparity between Poulton's observation and the present results may have been due to the differential heating. The ability to encapsulate a particular pattern of results and reconcile apparently contrasting data has particular appeal and appears to be the strongest element of the behavioral arousal hypothesis. However, in essence, it represents its greatest weakness. There seems to be few results that this account cannot encapsulate in a post hoc manner. In contrast, the arousal hypothesis rarely predicts performance capability in specific circumstances, and it is on this ground that it has been criticized (Hancock, 1983, 1987; Hancock & Warm, 1989). Poulton (1976) has perspicaciously observed that, although he espoused the arousal account, it is ultimately unsatisfactory. He noted that an arousal account of temperature and performance may not be very good, but it is the best available. However, there are two viable alternative accounts, each based on the respective notions that individual factors may exert common actions across stressors or that body temperature itself exerts a discrete effect.

The latter position emanates from the foundational work of Kleitman (1939/1963), who found that efficiency on differing mental and psychomotor tasks was highly responsive to change in body temperature. That is, as body temperature increased during the diurnal cycle, so did efficiency. More recent work by Allan and his colleagues has suggested that when body temperature is elevated above a threshold level, usually in the region of the peak absolute value for the circadian rhythm, then the increase in speed of performance is offset by the ascending error rate (Allan, Gibson, & Green 1979; Nunneley, Reader, & Maldonado 1982). These observations suggest that the level of deep body temperature controls the rate of performance, whereas skin temperature, through its influence on comfort, mediates the absolute accuracy level of such performance. This approach has been augmented by the recent work in selective head heating, which implies that the beneficial effect of increasing rate may be realized without subject discomfort and, consequently, increased error rate.

The second alternative behavioral account is somewhat more peripheral with respect to the present work than is either the arousal or direct body temperature proposals. Wilkinson (1969) indicated that a variety of factors exert a common influence across several stressful situations. He identified duration of performance, familiarity with the stressor and task, level of stress, level of subject motivation, and presence or absence of alternate stressors as most important. He claimed that these factors are influential across several stressors, including heat and cold stress. This notion of important common factors was used by Hancock (1983) in an account of performance under selective head heating. That study suggested that actual temperature increase and task complexity interact to affect performance capability. The implication from the present results is that temperature elevation must exert a primary influence in any such interaction. Each of these accounts indicates a relationship between the relative physiological state of performers and the action in which they are engaged. In summary, the behavioral findings from the current work indicate two important points. First, change in performance rate appears more responsive to the temperature change than to the complexity of the task. Second, the relationship between speed of performance and temperature change is not necessarily a simple one.

Physiological Analysis

If the notion of unitary behavioral arousal is rejected, it is still necessary to seek an account on the behavioral level of the phenomena at hand. To facilitate such a search, the precise physiological effects of the head heating and cooling need to be examined. The first and salutary point to note is that at the current time little is known concerning the physiological effects of selective head heating (see Nunneley, et al. 1982), particularly when the subject occupies a comfortable thermal environment. An initial problem concerns the measurement site. It is uncertain whether the tympanic membrane reflects precise fluctuations of temperature in the head core. While Benzinger (1969) advocated membrane temperature as just such a measure, actual sensor-membrane contact is painful and there is a possibility of tissue damage. Consequently, prolonged observation is both difficult and potentially dangerous, and subject discomfort may interrupt performance. In the present experiments, temperature was measured in the auditory canal adjacent to the membrane. Cooper, Cranston, and Snell (1964) suggested that, although absolute temperature presents a gradient down the wall of the meatus, the site still represents central temperature change. More recently, Greenleaf and Castle (1972) and Nadel and Horvath (1970) indicated the measure may be influenced in part by skin temperature. However, at the current time, the deep meatus still represents the most suitable and acceptable measurement site for selective head temperature change.

Most previous investigations concerning the effect of an abnormal temperature difference between the head and the rest of the body have taken the form of physiological inquiries into the effectiveness of head cooling to alleviate whole body heat stress during exposure to high ambient temperature (Brown & Williams, 1982; Nunneley, Troutman, & Webb, 1971). Such cooling has been shown to facilitate comfort (Brown & Williams, 1982) and aspects of cognitive performance (Konz & Gupta, 1969; Nunneley, et al. 1982). The process of regulation under such differential conditions has been investigated by Marcus (1973), who suggested that heating specific areas of the scalp could affect temperature in the deep meatus. Marcus indicated that this result would have to be accomplished by some property of the circulatory system, for he found that changes of equivalent temperature of heating pads placed below the external pinna had no affect on meatus temperature, compared with the relatively large change when such pads were superior to the pinna. His data did not allow him to distinguish between possible counter-current heat exchange or the direct action caused by venous flow in areas adjacent to the membrane. Counter-current heat exchange as a mediational thermoregulatory mechanism was suggested by McCaffey, Geis, Chung, and Wurster (1975) in their experiments on selective head heating. They suggested that the process corresponds to that noted in other species in which the proximity of major veins and arteries allows local heat exchange, thereby facilitating thermal stability. Clearly, the physiological effects of selective head-temperature variation need to be examined in more detail.

A Temperature-Based Account

Although the precise physiological actions that are engendered by heating are as yet unclear, it is possible to propose a behavioral account purely on the basis of temperature change. This account would follow, in part Broadbent's (1963) indication that temperature, as a potential influence on performance, acts through its own discrete system. The present results help to account for a previous disparity in findings observed under selective head heating. For example, Holt and Brainard (1976) found choice reaction time and visual search time to be reduced under an elevation of 1.11°C. However, in contrast, Hancock and Dirkin (1982) reported that central and peripheral visual choice reaction time was slower but more accurate under an elevation of approximately 0.5°C. Subsequently, Hancock (1983) found that a simple mental task was facilitated by a 1.01°C increase in temperature, measured in the deep meatus. The present results indicate an initial trend toward elevated estimation with a mild increase in temperature and a subsequent reduced estimation under a higher temperature. This pattern perhaps implies that variation in temporal estimation subsumes the above task responses or, as is more likely, some common mediational mechanism responsive to variation in head temperature underlies such behavioral actions.

With such a perspective, it is possible to examine the chemical clock hypothesis as proposed by Hoagland (1933) and as tested by the present experimental procedure. The tenet of this hypothesis is an inverse linear relationship between head temperature and time estimation. This general tendency has been accepted by several previous investigations concerning whole body temperature and perceived duration (Baddeley, 1966; Bell, 1965, 1966, 1975, 1977; Fox, Bradbury, Hampton, & Legg, 1967; Green & Simpson, 1977; Kleber, Lhamon, & Goldstone, 1963). However, this hypothesis was not supported without some caution for the linear nature of the relationship. If the present findings are taken as a rejection of the linear function, they imply that the relationship between perceived duration and temperature is not a simplistic one and cannot be described completely by the Arrhenius equation as previously thought.

The second hypothesis concerns the consistency of individual responses and requires that prescribed changes in head temperature be accompanied by prescribed changes in the perception of duration. With regard for variation in absolute values along both axes for different individuals, the hypothesis concerning consistency is supported here. Such consistency is important, for it indicates a diminished role for possible asymmetric transfer effects. These latter effects are due to the inappropriate transfer of situational strategies in repeated measures designs (Poulton, 1973). Briefly, this position suggests that the use of a within-subject design, in which repetitive performance on the same task is required under differing conditions, is vulnerable to a methodological artifact. The subject adopts an overt or covert strategy in either a control or a stress condition that is inappropriately transferred to the obverse condition. This effect is particularly evident in designs employing multiple stressors (Poulton & Edwards, 1974). The consistent pattern of results for each subject in the present work suggests this was not an influential factor, and may be due to two circumstances. First, the actual manipulations were not perceived as stressful by the subjects. Second, subjects were provided with an overt strategy prior to experimental manipulations in which they counted quietly to themselves while estimating each individual period.

The notion of the chemical clock implies a strong parallel between the physiological change and variation in the temporal percept. Such a notion depends on affirmation of both the primary and secondary hypotheses just described. It is important to note that unlike previous accounts (e.g., Bell, 1966) the chemical clock hypothesis was not rejected on the basis of individual's inconsistency of response, but rather on the failure to find a linear relationship. This was perhaps due to the use of selective head temperature manipulation rather than whole body heating and cooling previously employed (Bell, 1975; O'Hanlon, McGrath, & McCauley, 1974). However, the results consequently imply some temperature-sensitive mechanism that is responsive to a threshold elevation. The precise physiological change that might constitute such a threshold, be it absolute temperature or some thermoregulatory action in the cortex based on rate of change of temperature, is not immediately apparent from the present results.

One major difference in the present manipulation is that previous investigations exclusively examined whole-body temperature variation. That differing results have been observed for similar tasks under comparable elevations has already been noted. However, how much of the disparity was due to varying the manipulation may not be directly determined. This does not deny the initial postulation that if the chemical clock is located in the cortex, the local heating manipulation is a more parsimonious test of the hypothesis. However, the criticism advanced concerning remote sites of measurement used by previous investigators (e.g, Bell, 1975) should be considered with respect to the current work. The relative validity of auditory meatus as a site for monitoring head core temperature change has been discussed. It is possible that this temperature measurement site is relatively insensitive with respect to changes in temperature level at the site of the mechanism responsible for temporal perception. Although more sophisticated methods of measurement are available (e.g., Lassen, Ingvar, & Skinhoj, 1978), it is likely that temporal perception is not accomplished by some discrete mechanism, but rather is an attribute of distributed elements of the central nervous system.

Understanding temperature effects on the speed of performance extends beyond the time perception realm and provides an explanatory account of some interesting observations. In particular, Baker and her colleagues (Baker, Holding, & Loeb, 1984; Baker, Quinkert, Holding, & Colquhoun, 1989) noted that the circadian rhythms in performance capability differ between men and women (see also Aschoff, 1984). This differentiation in performance is mirrored by differences in individual temperature rhythms (see also Hancock, 1983). In a recent se of experiments, Hancock, et al. (1992) showed that time perception for men an women follow their respective rhythms. However, the rhythm for women subject showed an earlier peak then that of men, and this phase-lagging effect has a important influence. That is, combining data across men and women at specifi times can erase certain performance influences because the mutual interference of rhythms can result in a wash-out effect. This is a critical observation because many experimental procedures specifically test subjects at the same time of day and include both men and women in their sample. Consequently, disproportional sampling, or testing at different times of day may result in differing patterns of performance results. These effects appear to be subsumed by body temperature influences on a central temporal mechanism frequently, if unadvisedly, referred to as an internal clock.

There is a subsidiary hypothesis that pertains to previous investigations of temporal perception. The controversy concerning the complexity of the stimulus and the perception of duration relates to the proposal by Ornstein (1969) and Priestley (1968). Ornstein contended that, as display complexity increases, the perception of its duration is linearly reduced, whereas Preistley maintained the reverse. Hogan (1978) claimed to have reconciled such views by an appeal to the notion of individual subject differences. These investigations presented visual and auditory stimuli of varying complexity as independent variables. In the present work, the subject was sound and light isolated; consequently, the complexity emerged from the manner of producing responses rather than an observed or heard display. Results suggest a marginal effect in which the filled manipulation produced shorter times than the unfilled comparator. Initially, this would imply some degree of support for Ornstein's position, even though "complexity" had only two levels and thus linearity could not be reliably deduced. The marginal effect for filling, as compared with previous substantive effects (see Doob, 1971), is attributed primarily to the motoric nature of the present demand.

Summary and Conclusions

It remains to make explicit what the present study has to say concerning the problem of endogenous and exogenous control of human temporal perception. When individuals function in a societal group some adherence to an external and consistent referential system is mandatory. Doob (1971) labels this adherence chronometry. The arbitrary metric in Western society is the decay rate of cesium, and the initial referential spatial point is the meridian through the Greenwich Observatory in England. Despite the priority of this system in assessing temporal intervals, this is not real time, merely an acceptable arbitrary reference. The rate of the passage of time experienced by individuals without reference to this system may vary greatly. It is on this latter basis that Hoagland objected to Sir James Jeans's view of time as a homogeneous medium of consistent rate, essentially an affirmation of the Newtonian construct.

That time and space are veridical phenomena is a metaphysical inquiry. However, it is the case that time and space are phenomena relevant to the structuring of the environment that allows organisms to function. Most investigators concerned with temporal perception have avoided the essential interdependence of time and space and the largely intractable behavioral problems associated with such philosophic inquiry. The essence of the present work is the examination of an endogenous metric of the perceiver by examining how variation in this metric may affect the perception of brief temporal intervals, below 1 min. Although chronal time is used as a form of measure, it is merely a referential comparison. In terms of psychological operations during brief periods, the external clock is of restricted utility. Various psychological investigators have affirmed that in such modes of perceiving, temporal information is governed solely by assimilation of impinging environmental stimuli. This argument is buttressed by empirical demonstrations of the potency of stimulus rate and complexity on the perception of brief intervals and the dearth of evidence for alternate physiological correlates. In the present experiments head temperature was systematically manipulated, and the data favor the presence of some endogenous metric operating beyond some threshold temperature value.

The nonlinear effect observed is disturbing for a simplistic endogenous position. If only data from the control and severe heat conditions were selected, the 1°C increase in temperature would be accompanied by a 10% increase in the speed of estimation. This would represent a doubling in rate for an extrapolated 10°C range, a figure highly consistent with many biological functions. However, like Hoagland's transformation of Francois's data, the use of only two data points is highly seductive for a subsequent linear interpretation of the effect. The question remains, how does the nonlinearity address an endogenous metric? First, it is possible that the measurement site may not veridically reflect changes in the core temperature, and thus the relationship is somewhat obscured by a potential artifact. Without superior measurement equipment, this remains a point of speculation. More serious, in terms of an endogenous metric, it suggests a relative insensitivity in the middle range of possible human core temperature variation. The absence of an effect with such temperature change is apparently also reflected in previous investigations on the circadian rhythm of temporal estimation. Few studies of such an effect have been reported (see Hancock, et al. 1992; Pfaff, 1968; Thor, 1962). One reason for the lack of decisive evidence on this subject may be the relative insensitivity in the experienced temperature range as noted.

Some form of compromise between the endogenous and exogenous positions appears possible. Consider the notion proposed by Fox et al. (1967) of time perception as a learned ability. Clearly, in the absence of chronal information, endogenous stimuli exert a primary role. The potential exists for an important interac tion between external information and some central mechanism of the perceive that is thermally sensitive beyond some threshold level (see Treisman, 196 1984). The latter system appears thermally sensitive in some nonsimplistic mar ner. The consistency of response of each of the subjects is encouraging in sug gesting some ubiquitous phenomenon across individuals and indicates the nee to pursue such a relationship further.

The results from the present work fail to support the notion of a simplistic isomorphic relationship between temperature and the estimation of short-term temporal durations. The current manipulation varies from the more traditional perturbations of whole body temperature. The rejection of the chemical clock hypothesis is based on its failure to fulfill the criteria of an inverse linear relationship between time and temperature and not on the basis of individual inconsistency, as all previous rejections of the theory have been founded (cf. Bell, 1966). The consistency of results implies some temperature-sensitive mechanism that responds beyond some threshold value, although the physiological changes that induce such a threshold violation may not be readily determined from the current results. The relative insensitivity of temporal estimation to mild perturbations in head temperature may address the continuing equivocation concerning a circadian variation in the estimation of short intervals (Pfaff, 1968; Thor, 1962). Such an assertion is open to more thorough and directed empirical investigation. How an endogenous mechanism may interact with certain cognitive functions, previously demonstrated to affect the perception of duration (Ornstein, 1969), remains an unknown but fruitful area for continuing investigation.

REFERENCES

Allan, J. R., Gibson, T. M., & Green, R. G. (1979). Effect of induced cyclic changes of deep body temperature on task performance. *Aviation, Space and Environmental Medicine, 50,* 585–589.

Anliker, J. (1963). Variations in alpha voltage of the electroencephalogram and time perception. *Science, 140,* 1307.

Aschoff, J. (1984). Circadian timing. In J. Gibbon and L. Allan (Eds.), *Timing and time perception* (pp. 442–468). New York: New York Academy of Sciences.

Axel, R. (1924). Estimation of time. *Archives of Psychology,* No. 74.

Baddeley, A. D. (1966). Time estimation at reduced body temperature. *American Journal of Psychology, 79,* 475–479.

Baker, M A., Holding, D. H., & Leob, M. (1984). Noise, sex, and time-of-day effects in a mathematics task. *Ergonomics, 27,* 67–80.

Baker, M. A., Quinkert, K., Holding, D. H., & Colquhoun, W. P. (1989). *Time-of-day and female temperature as factors in performance.* Southern Society for Philosophy and Psychology, New Orleans, LA.

Bell, C. R. (1965). Time estimation and increases in body temperature. *Journal of Experimental Psychology, 70,* 232–234.

Bell, C. R. (1966). Control of time estimation by a chemical clock. *Nature, 210,* 1189. 1190.

Bell, C. R. (1975). Effects of lowered temperature on time estimation. *Quarterly Journal of Experimental Psychology, 27,* 531–538.

Bell, C. R. (1977). Time and temperature a reply to Green and Simpson. *Quarterly Journal of Experimental Psychology, 29,* 341–344.

Benzinger, T. H. (1969). Heat regulation: Homeostasis of central temperature in man. *Physiological Reviews, 49,* 671–759.

Bindra, D., & Waksberg, H. (1956). Methods and terminology in studies of time estimation. *Psychological Bulletin, 53,* 155–159.

Broadbent, D. E. (1963). Differences and interactions between stresses. *Quarterly Journal of Experimental Psychology, 15,* 205–211.

Brown, G. A., & Williams, G. M. (1982). The effect of head cooling on deep body temperature and thermal comfort in man. *Aviation, Space and Environmental Medicine, 53,* 583–586.

Clausen, J. (1950). An evaluation of experimental methods of time judgment. *Journal of Experimental Psychology, 40,* 756–761.

Cooper, K. E., Cranston, W. I., & Snell, E. S. (1964). Temperature in the external auditory meatus as an index of central temperature changes. *Journal of Applied Physiology, 19,* 1032–1035.

Doob, L. W. (1971). *Patterning of time.* New Haven: Yale University Press.

Dureman, I., & Edstrom, R. 1964. *EEG and time perception.* Technical Report No. 22, University of Uppsala, Sweden, 1964.

Fox, R. H., Bradbury, P. A., Hampton, I. F. G., & Legg, C. F. (1967). Time judgment and body temperature. *Journal of Experimental Psychology, 75,* 88–96.

Francois, M. (1927a). Contribution a l'etude du sens du temps. La temperature interne comme facteur de variation de l'appreciation subjective des durees. *Annee Psychologie, 28,* 186–204.

Francois, M. (1927b). Influence de la temperature interne sur notre appreciation du temps. *C. R. Soc Biology, 108,* 201–203.

Gilliand, A. R., Hofeld, J. B., & Eckstrand, G. (1946). Studies in time perception. *Psychological Bulletin, 43,* 162–176.

Green, T. R. G., & Simpson, A. J. (1977). Time and temperature: A note on Bell. *Quarterly Journal of Experimental Psychology, 29,* 337–340.

Greenleaf, J. E., & Castle, B. L. (1972). External auditory canal temperature as an estimate of core temperature. *Journal of Applied Physiology, 32,* 194–198.

Grether, W. F. (1973). Human performance at elevated environmental temperature. *Aerospace Medicine, 44,* 747–755.

Hancock, P. A. (1981). Heat stress impairment of mental performance: A revision of tolerance limits. *Aviation, Space and Environmental Medicine, 52,* 177–180.

Hancock, P. A. (1982). Task categorization and the limits of human performance in extreme heat. *Aviation, Space and Environmental Medicine, 53,* 778–784.

Hancock, P. A. (1983). The effect of an induced selective increase in heat temperature upon performance of a simple mental task. *Human Factors, 25,* 441–448.

Hancock, P. A. (1987). Arousal theory, stress and performance: Problems of incorporating energetic aspects of behavior into human-machine systems function. In L. S. Mark, J. S. Warm, & R. L. Huston (Eds.), *Ergonomics and Human Factors: Recent Research.* (pp. 170–179). New York: Springer-Verlag.

Hancock, P. A., & Dirkin, G. R. (1982). Central and peripheral visual choice-reaction time under conditions of induced cortical hyperthermia. *Perceptual and Motor Skills, 54,* 395–402.

Hancock, P. A., Vercruyssen, M., & Rodenburg, G. J. (1992). The effect of gender and time-of-day on time perception and mental workload. *Current Psychology: Research and Reviews, 11,* 203–225.

Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors, 31,* 519–537.

Hoagland, H. (1933). The physiological control of judgments of duration: Evidence of a chemical clock. *Journal of General Psychology, 9,* 267–287.

Hogan, H. W. (1978). A theoretical reconciliation of competing views of time perception. *American Journal of Psychology, 9,* 417–428.

Holt, W. R., & Brainard, E. C. (1976). Selective hyperthermia and reaction time. *Perceptual and Motor Skills, 43,* 375–382.

Kleber, R. J., Lhamon, W. T., & Goldstone, S. (1963). Hyperthermia, hyperthyroidism and time judgment. *Journal of Comparative and Physiological Psychology, 56,* 362–365.

Kleitman, N. (1939/1963). *Sleep and wakefulness.* Chicago: University of Chicago Press.

Konz, S. A., & Gupta, V. K. (1969). Water cooled hood affects creative productivity. *American Society of Heating, Refridgeration and Air-Conditioning Engineers Journal, 7,* 40–43.

Langer, J., Wapner, S., & Werner, H. (1961). The effect of danger upon the experience of time. *American Journal of Psychology, 74,* 94–97.

Lassen, N. A., Ingvar, D. H., & Skinhoj, E. (1976). Brain function and blood flow. *Scientific American, 239,* 62–71.

Mackworth, N. H. (1950). *Researches on the measurement of human performance.* Medical Research Council Special Report, Series 268. London: HMSO.

McCaffrey, T. V., Geis, G. S., Chung, J. M., & Wurster, R. D. (1975). Effect of isolated head heating and cooling on sweating in man. *Aviation, Space and Environmental Medicine, 46,* 1353–1357.

Nadel, E. R., & Horvath, S. M. (1970). Comparison of tympanic membrane and deep body temperature in man. *Life Science, 9,* 869–875.

Nichols, H. (1890). The psychology of time. *American Journal of Psychology, 3,* 453–529.

Nunneley, S. A., Reader, D. C., & Maldonado, R. J. (1982). Head-temperature effects on physiology, comfort, and performance during hyperthermia. *Aviation, Space and Environmental Medicine, 53,* 623–628.

Nunneley, S. A., Troutman, S. J., & Webb, P. (1971). Head cooling in work and heat stress. *Aerospace Medicine, 42,* 64–68.

O'Hanlon, J. F., McGrath, J. J., & McCauley, M. E. (1974). Body temperature and temporal acuity. *Journal of Experimental Psychology, 102,* 788–794.

Ornstein, R. E. (1969). *On the experience of time.* Middlesex, England: Penguin.

Pepler, R. D. (1958). Warmth and performance: An investigation in the tropics. *Ergonomics, 2,* 63–68.

Pfaff, D. (1968). Effects of temperature and time of day on time judgments. *Journal of Experimental Psychology, 76,* 419–422.

Pieron, H. (1923). Les problemes psychophysiologiques de la perception du temps. *Annee Psychologie, 24,* 1–25.

Pieron, H. (1945). *The sensations: Their functions, processes and mechanisms.* London: Muller.

Poulton, E. C. (1973). Unwanted range effects from using within-subject experimental designs. *Psychological Bulletin, 80,* 113–121.

Poulton, E. C. (1976). Arousing environmental stresses can improve performance, whatever people say. *Aviation, Space and Environmental Medicine, 47,* 1193–1204.

Poulton, E. C. (1977). Arousing stresses increase vigilance. In R. R. Mackie (Ed.), *Vigilance: Theory, operational performance and physiological correlates,* New York: Plenum Press.

Poulton, E. C., & Edwards, R. S. (1974). Interactions and range effects in experiments on pairs of stresses: Mild heat and low frequency noise. *Journal of Experimental Psychology, 102,* 621–628.

Poulton, E. C., & Kerslake, D. McK. (1965). Initial stimulating effect of warmth upon perceptual efficiency. *Aerospace Medicine, 36,* 29–32.

Preistley, J. B. (1968). *Man and time.* New York: Dell.

Schaefer, V. G., & Gilliland, A. R. (1938). The relation of time estimation to certain physiological changes. *Journal of Experimental Psychology, 23,* 545–552.

Selye, H. (1956). *The stress of life*. New York: McGraw-Hill.

Surwillo, W. W. (1966). Time perception and the "internal clock": Some observations on the role of the electroencephalogram. *Brain Research, 2,* 390–392.

Thor, D. H. (1962). Diurnal variability in time estimation. *Perceptual and Motor Skills, 15,* 451–454.

Treisman, M. (1963). Temporal discrimination and the indifference interval: implications for a model of the internal clock. *Psychological Monographs, 77* (Whole No. 576).

Treisman, M. (1984). Temporal rhythms and cerebral rhythms. *Annals of the New York Academy of Sciences, 423,* 542–565.

Wallace, M., & Rabin, A. I. (1960). Temporal experience. *Psychological Bulletin, 57,* 213–236.

Werboff, J. (1962). Time judgment as a function of electroencephalographic activity. *Experimental Neurology, 6,* 152–160.

Wilkinson, R. (1969). Some factors influencing the effect of environmental stressors upon performance. *Psychological Bulletin, 72,* 260–272.

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