Human Adaptation to Work in Two Different Climates

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The processes of acclimation to hot-dry and to warm-humid climates were studied using two approaches: a quantitative analysis of literature data and an experimental study in the laboratory concerning the physiological parameters of heart rate, rectal temperature, sweat loss, and subjective assessment.

Analysis of literature data: Data from 62 experiments with a total of 813 participants were pooled and recalculated. The experiments ranged from 6 to 24 days, air temperatures from 30.4 to 50.0 °C, water vapor pressures from 1.5 to 6.5 kPa, and wet bulb globe temperatures (WBGT) from 27.4 to 38.6 °C.

Laboratory studies: In the laboratory, 8 participants were acclimated during 15 consecutive days to a hot-dry climate and to a warm-humid climate, which were equivalent in terms of the WBGT (33.5 and 33.6 °C, respectively). The participants walked four times for 25 min on a treadmill at a speed of 4 km/h. The hot-dry climate caused somewhat greater strain than the warm-humid condition. In the course of acclimation to the hot-dry climate, heart rate and rectal temperature started at higher levels, decreased slightly steeper but remained on a higher level throughout. Nevertheless, the differences between both thermal conditions were small, and both physiologic functions reached the point of acclimation almost at the same time under warm-humid and under hot-dry exposure. Sweat loss, which is not regarded as a valid predictor for acclimation, was considerably higher but increased less in the hot-dry than in the warm-humid climate.

1. INTRODUCTION

The ability to adapt to a wide range of environments is an essential prerequisite for life, and this most fascinating phenomenon has been extensively proved for numerous physiologic functions.

Abrupt exposure to heat, whether experienced when travelling to hot countries or when working in the heat (e.g., mines, glass manufacturing), strains the organism and reduces the available reserves of physical capacity. But humans are able to adapt, for example, initially increased heart rate and rectal temperature decrease, whereas sweat loss increases gradually. Concomitantly, the reserves of physical capacity increase again. Numerous studies on this topic were executed within the last 5 decades. The process of acclimation—which is generally the same in different climates—was described in detail, and the physiologic mechanisms are sufficiently known, at least with regard to industrial safety.

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Despite this, there are still unsolved problems. A question concerns the quantitative differences between qualitatively different climates. A more efficient and faster acclimation was reported to hot-dry than to warm-humid climates, and vice versa (Fox, Goldsmith, Hampton, & Hunt, 1967; Henane, 1981).

It is difficult (if not impossible) to answer this question on the basis of the individual publications, as there are scarcely two studies that are easy to compare. It is true that most studies were executed with young male participants and that at least heart rate, rectal temperature, or sweat loss were recorded, but—among other things—the climates the participants usually were adapted to, experimental thermal stress, daily exposure time, duration of the experiments, type of exercise, workload, and clothing insulation, varied extremely.

This article contributes to the question whether the course and extent of acclimation depend on the specific composition of the thermal factors. For this particular problem, two different climates, warm-humid and hot-dry, were chosen, and two approaches were applied: a quantitative analysis of the literature and a directed experiment in the laboratory.

2. QUANTITATIVE ANALYSIS OF THE LITERATURE

Despite highly diverging results and conclusions in the individual papers, it is nevertheless presupposed that the majority of studies were thoroughly planned and executed. So, it should be possible to pool the data from different studies and to analyse them using multifactorial statistic methods to enable valuable conclusions and founded hypotheses for further research.

2.1. Material and Methods

Publications since 1943 were studied, and papers that fulfilled the following criteria were selected:

- Methods of registration and evaluation were well described.
- Thermal stress (air temperature, humidity, velocity), including daily exposure and duration, and interruptions of the experiments were exactly declared.
- Sex and number of participants were presented.
- At least, either heart rate, rectal temperature, or sweat loss was registered.
- The results were quantitatively presented in tables or figures, separately for each day.

All together, 33 papers (cited at the end of the reference list) fulfilled these criteria; most of them presented additionally clothing insulation and workload. They covered 62 experiments with 813 participants (among them 17 female). The respective results were pooled and used for a summarizing calculation.

2.1.1. Data Processing

**Units.** Because different units were used in the individual papers, the data were first transformed into the following units: degrees Celsius (°C), kilo pascals (kPa), meters per second (m/s), and watts (W).

**Thermal indices.** The thermal parameters varied extremely. For a better assessment of thermal stress, the most widespread index for heat, the wet bulb globe temperature (WBGT; International Organization for Standardization [ISO], 1989a) was calculated. A more complex index, such as the required sweat rate (Ereq; International Organization for Standardization [ISO], 1989b), was not determined, as clothing insulation and workload were not always declared.

**Characteristic thermal situations.** Though the terms hot-dry and warm-humid are frequently used, they are not clearly separated. To avoid an arbitrary decision, air temperatures of the 62 experiments were plotted against their water vapor pressures (Figure 1). By a cluster analysis
Figure 1. Cluster analysis for the separation of hot-dry and warm-humid climates in 62 experiments with overall 813 participants.

(average-linkage method), three climates were separated according to these variables. They were classified as neutral, warm-humid, and hot-dry.

Compressing the duration of the experiments. Some experiments were interrupted for 1 or even 2 days during the weekends. The supposition of some authors that deacclimation takes place during this time (e.g., Wenzel & Piekarski, 1985) was statistically proven, but the effect was considered negligible. So, interruptions were discarded, and the data were compressed and treated as if daily recorded without interruptions. This procedure pretends shorter durations of the experiments.

The course of acclimation. Experiments with at least 6 data points were used to describe the course of acclimation. Due to the various durations of experiments, which rarely exceeded 12 days, presentations of heart rate and rectal temperature were restricted to 12 days (data points). Sweat loss was presented for 10 days (data points), as this variable was registered for more than 10 days in only one experiment. To make the experiments comparable, their results were standardized by subtracting the average of the individual experiment from its daily data points. To calculate the overall average, the data of the single experiments were weighted according to the square root of the number of participants, and a "middle growth curve" was calculated for each climate.

Determination of confounders. To determine the influence of various factors on the process of acclimation, a regression analysis was performed using experiments with a duration of at least 6 days. The differences between the first and the last values were taken as the suitable criterion.
2.2. Results

The general courses of acclimation are presented in Figures 2 to 4 for the warm-humid and hot-dry climates, separately for heart rate, rectal temperature, and sweat loss. Standard deviations or standard errors were not estimated or presented, as these data were often missed in the original papers. In general, heart rate and rectal temperature decreased, whereas sweat loss increased and the alterations between consecutive days became successively smaller (the ascents of the curves decreased gradually). The three physiologic variables behaved similarly in both climates. But heart rate and rectal temperature decreased less and sweat loss increased steeper in the warm-humid climate than in the hot-dry climate.

The fact that the distances between the physiologic parameters registered in both climates were small is related to standardization, which was performed by subtracting the average of each experiment from the daily data points so that the curves must cross each other.

The endpoint of acclimation is defined as the day of heat exposure, whereafter no further or only minor alterations occur and where the physiologic data level off. A biphasic model was applied and adapted to the curves of the physiologic parameters. Thereafter, the process of acclimation was finished for heart rate and rectal temperature after 5 to 8 days (Table 1). According to Figure 4, sweat loss increased gradually and reached the endpoint after about 9 days and in the hot-dry climate after 6 days (a calculated endpoint was not presented and probably not advisable as long as evaporation is unknown).

Influences on the process of acclimation. It was supposed that the courses of the physiologic parameters (heart rate, rectal temperature, sweat loss) are determined by daily exposure time, duration of the experiments, type of climate, thermal load, and workload.
A regression analysis was performed, and the $p$ values are listed in Table 2. According to these data, acclimation to warm-humid was determined by the duration of the experiments and by daily exposure as well. Workload was less important, and the relation with the thermal index WBGT was contradictory. Acclimation to hot-dry climate was not determined by any of these factors.

TABLE 1. Endpoints of Acclimation, Calculated From Literature Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Warm-Humid</th>
<th></th>
<th>Hot-Dry</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>7.5</td>
<td>$\pm$ 0.8</td>
<td>5.6</td>
<td>$\pm$ 0.4</td>
</tr>
<tr>
<td>Rectal Temperature</td>
<td>7.2</td>
<td>$\pm$ 0.4</td>
<td>7.3</td>
<td>$\pm$ 0.7</td>
</tr>
</tbody>
</table>
3. EXPERIMENTS ON ACCLIMATION TO A WARM-HUMID CLIMATE AND TO A HOT-DRY CLIMATE

The results of the literature outlined the necessities for the experimental study. The detailed requirements were:

- daily exposure and duration of the test series must enable full acclimation;
- thermal stress of both climates should be equally strenuous;
- though not essential, workload should be moderate in both climates.

### TABLE 2. Factors Influencing the Process of Acclimation, Calculated from Literature Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Warm-Humid</th>
<th></th>
<th></th>
<th>Hot-Dry</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HR</td>
<td>RT</td>
<td>SL</td>
<td>HR</td>
<td>RT</td>
<td>SL</td>
</tr>
<tr>
<td>Duration (days)</td>
<td>.030</td>
<td>.092</td>
<td>.028</td>
<td>.239</td>
<td>.219</td>
<td>.276</td>
</tr>
<tr>
<td>WBGT</td>
<td>.020</td>
<td>.362</td>
<td>.062</td>
<td>.220</td>
<td>—</td>
<td>.135</td>
</tr>
<tr>
<td>Daily Exposure</td>
<td>.024</td>
<td>.026</td>
<td>.210</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Workload</td>
<td>.299</td>
<td>.349</td>
<td>—</td>
<td>.042</td>
<td>.371</td>
<td>.486</td>
</tr>
<tr>
<td>Experiments (N)</td>
<td>19</td>
<td>19</td>
<td>20</td>
<td>23</td>
<td>17</td>
<td>14</td>
</tr>
</tbody>
</table>

Note. HR—heart rate; RT—rectal temperature; SL—sweat loss.
3.1. Material and Methods

3.1.1. Experimental Design
Defined work on the treadmill (4 km/h, 0°) was executed in two experiments of 15 consecutive days each, where the participants were exposed to either a warm-humid climate or to a hot-dry climate, which were equivalent in terms of the WBGT.

- warm-humid: $t_a = 37 \, ^\circ C$, $P = 4.40 \, kPa$, $v_a = 0.3 \, m/s$, $t_r = t_a$, WBGT = 33.5 °C.
- hot-dry: $t_a = 50 \, ^\circ C$, $P = 1.90 \, kPa$, $v_a = 0.3 \, m/s$, $t_r = t_a$, WBGT = 33.6 °C.

3.1.2. Participants
Both experiments were executed with 8 healthy participants (6 males, 2 females, 21–32 years). Seven participants participated in both series, but a complete loss of acclimation was guaranteed by an interval of at least 52 days between the experiments.

3.1.3. Experimental Procedure
The experimental procedure was as follows: First, the participants rested 10 min sitting in a neutral climate ($t_a = 22 \, ^\circ C$, Relative Humidity: 40–60%) and then another 10 min in the climatic chamber. Thereafter, they walked on a treadmill (4 km/h, inclination = 0°) during four successive 25-min periods and rested finally 15 min, again in the neutral climate. These periods were separated by breaks, the first lasted 5 min, the following, 3 min each.

3.1.4. Clothing and Fluid Supply
Male participants wore cotton shorts, socks, and gym shoes (0.1 clo), female participants additionally wore a T-shirt (0.2 clo). During the experiments, the participants received herb tea ad libitum. Individual consumption was exactly measured and regarded when sweat loss was calculated.

3.1.5. Physiological Parameters and Mood State
Heart rate and temperature were continuously recorded throughout the experiments. Heart rate was registered by means of the electrocardiogram, rectal temperature with thermistors (at a depth of 10 cm above the anus), and skin temperature was registered at three sites (forehead, chest, leg). Sweat loss was determined by weighing the participants with an accuracy of 5 g before and after the daily experiments as well as during each break and corrected by individual fluid intake. Whenever the participants were weighed they assessed their mood on suitable scales.

3.1.6. Ethic Recommendations
The experiments were carried out according to the ethic requirements. The participants were continuously observed by a physician and interrupted when excessive values were reached or when the participants refused to continue the tests. If rectal temperature exceeded 38.7 °C, the treadmill walk was terminated, but the participants stayed in the climatic chamber until the regular end of the daily experiment.

3.1.7. Treatment of the Data, Statistics
Statistical calculations based on total sweat loss during the daily experiments and on rectal temperature were averaged over the 25 min of the fourth working period. Cardiac strain was indicated by the difference between mean heart rate during the fourth working period minus heart rate recorded during the initial rest in the neutral climate (stress-related increase of heart rate).

The extent of acclimation achieved during the experiments was determined by comparing the averages of the initial 2 days with the respective averages of the final 2 days.

The Wilcoxon test or the $t$ test was applied to assess the daily differences between both thermal conditions. The more powerful Wald's test was applied to compare the overall courses of the physiological parameters in both climates.
The point of acclimation, whereafter no further significant alterations occur, was determined by means of a logistic function for heart rate and rectal temperature. A corresponding calculation for sweat loss makes less sense, because evaporation was not determined.

3.2. Results

3.2.1. The General Course of Acclimation

As demonstrated in Figure 5, heart rate and rectal temperature decreased gradually during the treadmill walk in the heat. The final data, however, remained on a considerably higher level as compared to appropriate experiments executed with the same participants in a thermally neutral condition (20 to 30 beats per min or 0.1 to 0.4 °C, respectively). On the contrary, sweat loss and temperature gradients between rectal and mean skin temperature increased during acclimation. In any case, the differences between consecutive days decreased gradually, and—apart from temperature gradients—the alterations between the initial and the final 2 days were significant for both climates, $p < .01$.

Regarding the endpoints of acclimation, heart rate levelled off after 3.5 to 4.5 days (stress-related increase after 6.1 to 8.1 days); rectal temperature needed more time and reached a steady state after 6.9 to 7.7 days (Table 3).

![Figure 5](image-url)

Figure 5. Averages and standard deviations (in only one direction) of rectal temperature, heart rate alterations, sweat loss, and temperature gradients during 15 daily experiments in a hot-dry and in a warm-humid climate. Eight participants each walked 4 times 25 min on a treadmill at a speed of 4 km/h.


### TABLE 3. Endpoints of Acclimation, Calculated From Experimental Data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Warm-Humid</th>
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<th>Hot-Dry</th>
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<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>3.5</td>
<td>$\pm$ 0.4</td>
<td>4.5</td>
<td>$\pm$ 0.3</td>
</tr>
<tr>
<td>Increase of HR</td>
<td>8.1</td>
<td>$\pm$ 1.3</td>
<td>6.1</td>
<td>$\pm$ 0.5</td>
</tr>
<tr>
<td>Rectal Temperature</td>
<td>6.9</td>
<td>$\pm$ 1.5</td>
<td>7.7</td>
<td>$\pm$ 0.7</td>
</tr>
</tbody>
</table>

*Note. p values estimated by the $t$ test between warm-humid and hot-dry climate were always greater than .05.*

#### 3.2.2. Acclimation to Different Thermal Conditions

Regarding the corresponding daily averages of rectal temperature and cardiac strain, no statistical differences were found between both climates, indicating the generally similar courses of the physiologic functions in both climates.

Visual inspection suggests that acclimation might be nevertheless influenced by the particular thermal stress. This is statistically confirmed by the Wald's test, which considers the single data and their specific temporal development. As the physiologic data were equal during initial rest in the neutral climate before exposures to warm-humid or hot-dry, differences between climates are probably related to the particular thermal stress.

Even the first exposure caused less elevations of rectal temperature and heart rate in the warm-humid condition than in the hot-dry condition. The values of both variables remained throughout the warm-humid climate below those recorded in the hot-dry environment, but the values in both climates narrowed each other. The temperature gradient increased slightly but significantly during acclimation to hot-dry; it was considerably larger but did not alter in the warm-humid climate. In the latter condition, sweat loss was about one third less but increased steeper than under the hot-dry exposure, the augmentation reached 19.2% (vs. 11.9% in the hot-dry condition).

Well-being (Figure 6) was initially better in warm-humid climate (high numbers) and failed to increase thereafter. The participants felt initially worse (low numbers) in the hot-dry climate, but mood increased gradually and significantly. At the end of the acclimation periods, mood reached the same level in both climates.

Regarding the endpoints of acclimation, heart rate and rectal temperature approached the steady state more rapidly in the warm-humid condition than in the hot-dry condition, but this difference was not significant.

Cardiac strain and rectal temperature were significantly correlated in both climates, $p < .01$. The respective regressions agreed highly (Akaike's information criterion), and the relation could be expressed by a single equation that is valid for both climates. These parameters correlated again on the 1% level with total sweat loss, but the respective ascents of the regressions differed considerably.

### 4. DISCUSSION

The aim of this article was to determine—if there are any—characteristic courses of and quantitative differences between acclimation to warm-humid and to hot-dry climates. Two approaches were used to solve this problem. First, the literature was analysed and the data of experiments comparable in method and evaluation were pooled, processed, and recalculated. Second, experiments were carried out in the lab where the participants were acclimated to either a warm-humid or hot-dry climate. As the wet bulb globe temperatures (WBGTs) were equal (33.5 °C, 33.6 °C, respectively), both climates are regarded as almost equally strenuous.
4.1. Methods
The data of overall 62 experiments with 813 participants published since 1943 were pooled and recalculated. Though the selection criteria were rather strict, a certain number of papers did not present clothing insulation, workload, or physical capacity of the participants. Contrary to the experimental data, it was, therefore, advisable to restrict the presentation of the results to relative data (e.g., Strydom et al., 1966).

Second, the lack of information about workload and clothing insulation prevented the determination of complex indices such as required sweat rate (Ereq), and so forth. Therefore, the WBGT, which only considers the physical climatic factors, was calculated to compare the climatic stress of the various climates.

In the experiments, daily heat exposure endured 122 min (10-min rest, 100-min treadmill walk, 12-min breaks). Even if critical values were exceeded, the participants stayed resting in the heat until the scheduled end of the experiments (or continued walking if rectal temperatures fell below 38.5 °C). This time was regarded as sufficient referring to systematic studies on optimal exposure times, which revealed that daily exposures of 100 min are enough to achieve acclimation during 9 or 10 days (Garden, Wilson, & Rasch, 1966; Lind & Bass, 1963).

4.2. The General Course of Acclimation
Numerous studies executed in the last 5 decades revealed that the process of acclimation in general is almost independent from the variation of the four thermal parameters (air temperature, humidity, velocity, radiant temperature). Initially, heat exposure increases heart rate, rectal temperature, and (insufficiently) sweat loss thereby limiting the reserves of physical capacity. During repeated or permanent exposure, heart rate and rectal temperature decrease and level off after a few days. Sweat loss increases further on and remains on a higher level.
The reserves of capacity then increase again, sometimes even to the baseline in temperate conditions.

This general course of acclimation was again verified in this study, by the first approach, the quantitative analysis of the literature, and by the second approach, the experimental work in the laboratory. In the experiments, full acclimation was achieved and statistically confirmed for heart rate and rectal temperature in both climates. But the final values shift to a higher plateau as compared to the same physical work executed in a neutral climate.

4.3. Acclimation to Different Thermal Conditions

The majority of studies published so far have dealt with acclimation exclusively to a single thermal condition. Very few authors compared acclimation to hot-dry climate with acclimation to warm-humid. Regarding sweat loss as the main criterion, their results and conclusions are contradictory. With respect to the literature, Rowel (1988) assumed from higher sweat rates a faster and better acclimation to hot-dry climate, whereas Henbane (1981), on the contrary, concluded from steeper increases that acclimation might be superior in warm-humid. Both conclusions are, however, not convincing, as these authors merely referred to dry and humid conditions, disregarding that the overall stress is determined by the combination of the four physical factors, clothing insulation, and workload. This aspect was particularly regarded in the present experiments. The climates applied here differed considerably, but the thermal stress was equal on the basis of the WBGT (ISO, 1989a). The WBGT values were 33.5 and 33.6 °C, respectively. Only Shvartz and coworkers (Shvartz, Benor, & Saar, 1972; Shvartz, Saar, Meyerstein, & Benor, 1973) executed experiments with two considerably different but equivalent climates in terms of the WBGT (35 °C). The authors who achieved the target climates with different methods and registered lower sweat rates in the warm-humid than in the hot-dry climate concluded that acclimation was better in the latter condition. Both an overall larger sweat loss and a smaller increase during acclimation to hot-dry climate were observed in the present experiments and were strongly confirmed by the quantitative analysis of the literature data. But it is certainly inadmissible to judge the process of acclimation only on the basis of sweat loss as high water vapor pressure prevents evaporation and increased sweat loss, is then less effective (Belding, 1972; Candas, Libert, & Vogt, 1980). This consideration is supported by the temperature gradient between rectal and mean skin temperature, which did not alter throughout exposure to humid heat, but which increased significantly during acclimation to the hot-dry climate, probably due to increased evaporation.

Throughout the hot-dry condition in the present experiments, heart rate and rectal temperature were above those of the warm-humid climate, suggesting that the latter climate might be somewhat less strenuous during acclimation. This assumption is supported by subjective well-being, which was on the average better in the warm-humid condition and which was significantly correlated with heart rate and rectal temperature. Mood was initially worse in the dry heat but increased gradually, reaching the same level as recorded in the warm-humid condition.

The endpoints of acclimation, whereafter no further alterations of the measured physiologic parameters take place, occurred first in the warm-humid climate, then in the hot-dry climate, suggesting that acclimation in the warm-humid condition might be somewhat superior to hot-dry.

However, the differences of acclimation observed in both climates are small, suggesting that the WBGT is a suitable measure even for physiologic functions. If so, a further question to be answered is whether—and if to what extent—acclimation to one of these climates is valid for the other. The verification of this hypothesis would imply that persons working in dry heat could be transferred without reservations to workplaces in warm-humid environments.
5. CONCLUSIONS

In two experiments, 8 participants were acclimated to either a warm-humid or a hot-dry climate, which were equivalent in terms of the WBGT. The fact that the physiologic functions revealed some differences and that the hot-dry condition seems to be slightly more strenuous suggests that the physiologic mechanisms that enable acclimation are somewhat different in both conditions and that it is probably inadmissible to estimate the process of acclimation on the basis of sweat loss alone.

Nevertheless, the differences between the two climates applied in the experiments are small. This supports the conclusion that the WBGT, which might not perfectly fulfill scientific requirements, is a suitable predictor of thermal strain for industrial purposes.

REFERENCES


ADDITIONAL REFERENCES

From which the literature data were drawn


