We compared responses in heart rate (HR), mean blood pressure (MAP), sweating rate (SR), sweating expulsion (SwE), and skin vascular conductance (VC) to mental task among different ambient temperature (Ta) conditions, i.e., 12, 16, 20, and 24°C. Seven subjects (27±5 yrs, 64±14 kg) underwent a 2-min color word conflict test (CWT) after 2 mins of baseline data acquisition following a 20-min resting period. All subjects wore long sleeve shirts and long pants. The skin blood flow was measured with a laser Doppler probe on the left index finger pulp to calculate skin VC, and the SR and sweating expulsion (SwE) were measured with a ventilated capsule on the left thenar. CWT significantly increased the HR and MAP, while there was no significant effect of Ta on the magnitudes of these responses. CWT significantly decreased the skin VC when the Ta was 24°C, whereas it significantly increased the skin VC when the Ta was 12 or 16°C. CWT significantly increased SR and SwE in all Ta conditions, and the SwE was greater in warmer conditions. These findings suggest that different ambient temperatures induce different responses in finger skin vasculature to mental task, implying the independent response of cutaneous vasomotor tone and sweat glands in glabrous skin to mental task.

However, we have limited information about the combined effect of mental task and Ta on these physiological responses. Considering previous studies, we can simply assume that the skin vasculature and sweating responses to mental task shift in parallel manner to the Ta. In fact, it was reported that the resting baseline value affected responses to emotional stress (Blair et al., 1959). Nevertheless, there are several reports arguing against this simple assumption. The Ta reportedly modulated the relationship between skin blood flow and sweating expulsion. Spontaneous and phasic decrease of the skin blood flow in the sole was observed without synchronization with sweating expulsion in a warmer Ta (29–40°C), whereas phasic increase of the blood flow with synchronization to sweating expulsion was observed at the same glabrous part in a cooler Ta during a mental task (22–29°C) (Sugenoya et al., 1995). This implies that different would be shown in SkBF, SR, and SwE responses to mental task. In addition, cutaneous arterioles are innervated solely by noradrenergic sympathetic vasoconstrictor nerves in glabrous regions of skin (no active vasodilator), whereas sweating is controlled via sympathetic cholinergic fibers (Kellogg, 2006). These imply differentiated control of skin blood vessels and sweating response to mental task.

An understanding of the pattern of responses to combined mental task and different Ta is important because the skin vessels and sweating respond to mental task, and thus could be relevant to assessing mental state in an applied field (e.g., Shimoda and Ikuta, 2005). We designed the present experiment...
to examine whether the skin blood vessels and sweating responses to mental task are affected by Ta. We hypothesized that a warmer Ta would augment the responses of SkBF, SR, and SwE. We observed SkBF, SR, and SwE in glabrous skin, heart rate (HR), and mean blood pressure (MAP) responses to mental task under different ambient temperatures.

Methods

Subjects

Seven subjects (4 males and 3 females, 27±5 yrs, 170±10 cm, 64±14 kg) participated in this study. All subjects were normotensive, not taking any medication, and had no history of autonomic dysfunction or cardiovascular disease. The Review Board of the Institution of Health Science, Kyushu University, Japan, approved the experimental protocol, and all subjects provided written informed consent to participate prior to the commencement of the study. All of the protocols used conformed to the Declaration of Helsinki.

Protocol

Subjects arrived at the laboratory after having abstained from exercise for at least 1 day, and from eating, smoking, and consuming caffeine for at least 2 hours. The experimental protocol was conducted in a quiet room with the subjects in a semirecumbent position. The subjects underwent a 2-min computerized color word conflict test (CWT; Stroop test) after 2-min baseline data collecting. A colored word (yellow, blue, green, purple, or red) written in an incongruent color was displayed on a computer monitor. The subject was instructed to click the color with which the word was indicated on the monitor. Prior to the test, each subject received instructions on how to perform the CWT, and practiced the test. The subject was also requested to make as good a score as possible. The test included 60 repetitions at 2-second intervals. The number of the correct answers was counted as the score of the CWT. All subjects were right-handed and they used the trackpoint on a laptop computer (IBM ThinkPad A21e) with the right hand to perform the CWT. No subject usually used a trackpoint. The ambient temperatures were set at 12, 16, 20, and 24°C. The experiments were conducted after a 20-min resting period to be acclimated to the ambient temperature. The experiment under each temperature was separated by more than five hours. Each subject completed all trials over two or three days. The order of trials was randomized. All subjects wore long sleeve shirts and long pants.

Fig. 1 Changes from baseline in mean arterial pressure (upper left), heart rate (upper right), skin vascular conductance (lower left) and sweating rate (lower right) are shown. The horizontal thick bars show the period of the CWT. The CWT significantly increased MAP, HR and SR from the baseline. The Ta significantly affected the relative changes of SR and skin CV response to the CWT. The skin VC significantly increased at 12 and 16°C, whereas it significantly decreased at 24°C in response to the CWT. The SEM is not shown for simplicity. *: significant difference vs. baseline value.
Measurements

HR, MAP, SkBF, and sweating responses were measured throughout the trial. The MAP was monitored every minute by an automatic sphygmomanometer (BP-306, Colin, Japan). The SkBF was continuously obtained from a laser Doppler probe on the left index finger pulp (ALF21, Advance). SR was measured from a glabrous area of the left thenar (Perspiro 201, Kentz). These variables were sampled at 100 Hz using an A/D converter (PowerLab 8e, ADInstruments). SwE during the CWT was counted by hand offline.

Immediately after the trial, the subjective sense of perceived temperature was asked. The subject made a tick on a 100-mm visual-analog scale, on the terminals of which very cold and very hot were written. Also they checked a 100-mm visual-analog scale of perceived stress. The scale was from no-stress to very stressful. These assessments were shown in units of mm from the side of cold or no-stress.

Data analyses

Data during the mental task (120–240 s) were averaged every 30-s while the baseline value was averaged for 2-min. SkBF was divided by MAP to assess the vascular conductance (VC). The trials were done over two or three days and probes of SkBF and SR were not applied at the same place. Thus we calculated the relative change from the baseline value in skin VC and SR while we calculated changes from the baseline value in HR and MAP. Data are expressed as mean±SEM values. To test the effects of the ambient temperature (16 to 24°C) and mental task (baseline and four 30-s bins during the CWT) on the response time course, the repeated measures ANOVA was performed by GLM procedure with the MANOVA and PRINTE options in an SAS package (version 8.2, SAS Institute, Cary, NC, USA). When a significant F value was obtained, Scheffe’s post-hoc test was used to detect the difference among Ta trials. To test the effect of the mental task, each value was compared to the baseline value by Dunnett’s test. To test the effect of Ta on SwE and the scores of the CWT and subjective sense, ANOVA and Dunnett’s test were used. The level of statistical significance was set at p<0.05. These statistical analyses were performed at the Computing and Communications Center, Kyushu University, Japan.

Results

Physiological responses

The Ta significantly affected the baseline HR but not MAP (Table 1). HR at 24°C was significantly higher than those at 12 and 16°C. We report the baseline values in skin VC and SR just for reference since we cannot guarantee these are obtained from completely the same place of the subject’s finger and thenar in all Ta conditions. The CWT significantly increased MAP and HR from the baseline in all Ta conditions, while there was no significant effect of Ta on these responses. The time course of SR was similar among different Ta conditions, while the baseline SR increased as Ta increased (Table 1). Ta significantly increased the SwE response to the CWT (Fig. 2), whereas no significant effect of Ta on the SR response to the CWT was obtained. SwE during the CWT was significantly different between 12 and 24, and 16 and 24°C.

The different Ta induced opposite skin VC responses to the CWT. The VC significantly increased at 12 and 16°C, whereas it significantly decreased at 24°C in response to the CWT. The Ta significantly affected the relative magnitudes of skin VC responses at 30–120 s of the CWT period. All subjects showed the same trend; at lower Ta the CWT increased skin VC and at higher Ta the CWT decreased skin VC.

Table 1 Baseline values at rest

<table>
<thead>
<tr>
<th>Ta (°C)</th>
<th>MAP (mmHg)</th>
<th>HR (bpm)</th>
<th>SR (mg/cm²/min)</th>
<th>Skin VC (ml/min/100 g tissue/mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>86.0±4.3</td>
<td>61.0±3.42</td>
<td>0.051±0.004</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td>16</td>
<td>82.0±4.2</td>
<td>61.1±3.24</td>
<td>0.065±0.004</td>
<td>0.11±0.03</td>
</tr>
<tr>
<td>20</td>
<td>87.5±7.1</td>
<td>69.2±4.1</td>
<td>0.080±0.007</td>
<td>0.44±0.13</td>
</tr>
<tr>
<td>24</td>
<td>80.9±5.4</td>
<td>71.0±4.02</td>
<td>0.093±0.004</td>
<td>0.47±0.09</td>
</tr>
</tbody>
</table>

A number of superscript denotes the significant difference compared to that at the Ta of the number.

Note that the SR and skin VC could not be obtained from completely the same place of subject’s finger and thenar in all Ta conditions.

Fig. 2 The SwE response to CWT is shown. ANOVA revealed that the Ta significantly affected the sweating expulsion rate response to CWT. *: significant difference.

Table 2 Score of CWT and subjective sense of temperature and stress

<table>
<thead>
<tr>
<th>Ta</th>
<th>Sense of temperature</th>
<th>Sense of stress</th>
<th>Score of CWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>11.0±4.3*</td>
<td>47.6±8.6</td>
<td>31.0±5.8</td>
</tr>
<tr>
<td>16</td>
<td>24.0±4.5*</td>
<td>52.7±5.7</td>
<td>29.8±4.9†</td>
</tr>
<tr>
<td>20</td>
<td>51.7±4.2*</td>
<td>40.4±7.8</td>
<td>36.2±5.3</td>
</tr>
<tr>
<td>24</td>
<td>75.6±3.0*</td>
<td>54.0±7.0</td>
<td>35.7±5.1</td>
</tr>
</tbody>
</table>

The sense of temperature and stress is 0–100 scale, and the score of CWT is 0–60 points.

*: significant difference vs. all other Ta conditions
†: significant difference vs. 20°C condition
The Ta affected the score of the CWT. The score at 20°C was slightly but significantly greater than that at 16°C. The subjective sense of temperature increased as ambient temperature increased. The Ta did not significantly affect the subjective sense of stress during CWT.

**Discussion**

The main finding of the present study was that Ta affects skin VC and SwE responses to the CWT. The response of the VC was opposite in colder and warmer conditions. The sweating and VC in glabrous (non-hairy) skin related to mental strain rather than thermoregulation (Matsuda et al., 1996). The present finding suggests that Ta also modulates sweating and VC responses in glabrous skin to mental task. In a Ta ranging from 22 to 29°C, glabrous SKBF on the sole of the foot reportedly related to sweating in the corresponding area (Sugenoya et al., 1995). We observed responses over a wider range than the previous study, and found different responses in skin VC and SwE.

The Ta clearly modified VC response to mental task; the VC increased in lower temperature whereas it decreased in higher temperature. This finding did not support our simple assumption that the VC and sweating responses to mental task shifts in parallel to the Ta, and in turn suggests that the VC response to mental task depends on the Ta. This implies that considering the ambient temperature is needed when one uses VC as an index of mental activities in applied physiological assessments.

The Ta modulated the SwE response to the CWT. Unlike the VC response, the effect of Ta on SwE was almost additive; Ta simply increased the sweating response to the CWT. The present finding suggests that the SwE response to mental activity is augmented by an increase in Ta. There are limited findings in sweating response to mental task when autonomic thermoregulation is needed at the same time. Ogawa (1975) reported that mental stimulation altered the SR not only in glabrous but also in nonglabrous skin, and at the same time, the mental stimulation decreased SR. On the other hand, it is well known that Ta alters SR in nonglabrous skin, in particular during exercise (Kondo et al., 2002). The present finding revealed that Ta alters SwE in glabrous skin during mental task as well as exercise.

Changes in VC, SR, and SwE are related to sympathetic activity. Sympathetic activity to skin vessels and sweat glands are generally similar (Estanol et al., 2004). However, different changes and regional differences in sympathetic activation were reported (Iwase et al., 1997; Kondo et al., 2003; Koba et al., 2006). Iwase et al. (1997) reported that the increase of sympathetic activity in the peroneal nerve is almost 200 % by heating, whereas that in the tibial is below 100 %. On the other hand, those in the peroneal and tibial were similar to the response of mental arithmetic. The different pattern of responses in VC, SR, and SwE in the present study implied a different pattern of sympathetic activation to skin vessels and to sweat glands.

Okamoto et al. (1994) compared the sudomotor and vasomotor components in skin sympathetic nerve activity in the tibial nerve, which innervates mainly glabrous skin, among Ta of 18 to 34°C. They found both sudomotor and vasoconstrictor components in tibial sympathetic activity suppressed as the Ta increases. Such a difference in skin sympathetic activity could have induced the different VC and SwE patterns in the present study, though there are no data on the combined effect of Ta and mental task.

Iwase et al. (1997) have shown the modified model from Ogawa and Sugenoya (1993) for a central mechanism of thermal and mental sweating and vasoconstriction. In this model, a mental activity facilitates the mental vasoconstrictor and sudomotor centers in glabrous skin, whereas warm stimulation to the thermoregulatory center, i.e., different Ta, seemed to facilitate the mental sudomotor center, whereas warm stimulation suppressed the vasoconstrictor center. We used Ta from 12 to 24°C, while previous studies used a warmer range. Thus the differences could be attributed to the different range of Ta used.

Of interest, the score of the CWT was affected by Ta. We cannot determine whether this change has significance in mental performance. Further studies are needed to test this. On the other hand, the subjective sense of stress was not affected by Ta. Thus we cannot attribute different physiological responses to a subjective sense of mental task among different Ta. In turn, we could assume an effect of repetition of the CWT on responses. Becoming skilled or getting familiar reportedly decreases SR (Matsuda et al., 1996). In the present study, however, the order of the trial was randomized and thus we can hardly explain the different response and score in different Ta conditions by considering a learning effect.

The present study has two limitations. First, we could not determine the effect of skin and core temperature in spite of the possible existence of the effect of body temperature on the responses. We could only refer to the effect of ambient temperature. Second, the sample size of subjects was relatively small. The possibility of type-one error might remain though we obtained statistically significant differences and the trends in the responses were similar in all subjects.

In summary, skin VC, SR, and SwE responses in glabrous skin to the CWT were compared among different Ta, i.e., 12, 16, 20, and 24°C. The CWT significantly increased the HR and MAP. The CWT significantly decreased the VC when the Ta was 24°C, whereas it significantly increased the CV when the Ta was 12 or 16°C. The CWT significantly increased SR and SwE in all conditions, while the SwE response to the CWT was significantly greater in warmer conditions. These findings suggest that Ta affects finger skin blood flow responses to mental task, implying the independent response of cutaneous vasomotor tone and sweat glands in glabrous skin to mental
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