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Effect of local thermal sensation on whole-body thermal sensation under stable non-uniform environment

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Abstract: To reveal the principles of human thermal responses and find out the effects of body parts on whole-body thermal sensation, through a subjective survey, experimental investigations on human responses are carried out when a single body part is thermally stimulated. Cooling airflow is sent to seven body parts, respectively. Totally 94 samples are tested. To eliminate the obvious multicollinearity of thermal sensation among different body parts, the principal component regression approach is adopted to obtain the principal components for the body parts under different experimental conditions. Through regression and analysis of principal components, the weighting factors of the seven body parts are obtained. A predictive model on whole-body thermal sensation is obtained based on the weighting factors. The results show that the different characteristics of trunk and limbs are clearly seen. The weighting factors of local thermal sensation are integrated values, and there is little difference among values of different body parts.

Key words: local thermal sensation; whole-body thermal sensation; non-uniform environment; weighting factor

For a long time, researchers have done much on thermal sensation under stable and uniform conditions, while little on that under non-uniform and transient conditions. Along with the appearance of new methods of air conditioning such as floor air supply systems[1], task-ambient air conditioning[2-3], and with the development of air conditioning in cars, the non-uniform thermal environment has been the research focus. Although there have been some achievements in this field, such as EHT[4], EQT[5], physiological evaluation on partial- and whole-body thermal sensation[2], and evaluation on automobile air conditioning[6], at present many subjective experiments are still required to establish the predictive model of thermal sensation.

Generally speaking, there are some main researches on the non-uniform environment including the relationship among micro-environmental parameters, local thermal sensation, local physiological parameters and the weighting factors of local thermal sensation. In this paper, the subjective experiments of stimulation on different body parts are used to discuss the effects of local thermal sensation on whole-body thermal sensation.

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1 Experiment

In consideration of the feasibility and universality of research, the body parts, such as head, chest, back, arm, leg and foot, are locally stimulated independently, which can also bring about notable experimental phenomena. Stimulated body parts and the method of stimulation are shown in Fig. 1. The experiments are performed in a controlled environment chamber where the air temperature and the humidity are controlled automatically with the precisions of ±0.5 ℃ and ±5%. In the ambient environment, an overhead mixing system is adopted and the wind velocity in the ambient area is less than 0.1 m/s, which means that the air flow in the ambient environment has little effect on the experiments. The local stimulation device consists of an air supply system and a partition device as shown in Fig. 1. The partition device includes a bracket and a screen, which can block off the light, heat, radiation and airstream. This device conducts the air flow to the simulated body part and keeps away from other parts. Furthermore, the screens are designed according to different body parts and will not affect the subjects' votes.

Fig. 1 Partition device

In this paper, local cooling ventilation is performed to simulate summer conditions, personal ventilation or automobile air conditioning. The ambient condition includes neutral and warm, and the local cooling condition is cool, as shown in Tab. 1. In the ambient environment, the relative humidity is controlled at 50% and the air velocity is less than 0.1 m/s. The air velocity at the outlet of local cooling ventilation is maintained at 1.5 m/s. The mean radiation temperature is approximate to the air temperature. Subjects are required to wear T-shirts and pants. Thus, the whole clothing thermoresistance is about 0.5 clo (Fig. 1 does not show clothes condition). During the test, the subjects do normal office work on computer.

Tab. 1 Experimental conditions

No.	Ambient condition	Ambient temperature /℃	Local cooling condition	Local cooling air temperature/℃
1	Neutral	26	Cool	20
2	Warm	30	Cool	20

There are totally 14 working conditions and one environmental condition with seven body parts stimulated. Ninety-four subjects are involved in the experiments and they are students. Among them, half are male and half are female. The personal information is shown in Tab. 2. Every subject is exposed to one or two experimental conditions, and there is no order for exposure. During the experiments, their good health, regular sleeping and normal meals and no acuity exercise are required to ensure that they are in good health. Before the experiments, the subjects are told about the vote procedure and then they can be familiar with the questionnaire. However, the detailed experimental conditions are confidential since their expectations will have some effects on the vote[7].

Tab. 2 Basic information of subjects

Age/year	Stature/cm	Avoirdupois/kg
25.5 ±6.5	171 ±18	63 ±25

The whole experiment lasted five months from June to October in 2008. Every experiment requires 80 min including 30 min for preparation, 20 min for sitting in the ambient environment and the last 30 min for local stimulation. In the ambient environment, subjects report their responses at 4 min intervals and during local cooling ventilation, 2 min intervals for the first 10 min and 5 min intervals for the following 20 min. After entering the chamber, subjects change their clothes and sit under the ambient condition. After they have been exposed for 20 min in the ambient environment, subjects begin to be stimulated. 30 min later, whether another body part will be stimulated depends on the will of the subjects. Before the second body part starts to be stimulated, another 20 min will be spent for recovery from former local stimulation. During the experiments, subjects are allowed to read and talk while they are forbidden to discuss vote results with each other. The vote scale adopts ASHRAE 7-point thermal sensation scale as shown in Tab. 3.

Tab. 3 Standard for TSV

Thermal sensation	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
TSV	+3	+2	+1	0	−1	−2	−3

2 Results

In this experiment, independence of sample is satisfied since the subjects are random and they do not discuss the related information about the experiment. By the S-W test of normality, all the thermal responses under different conditions satisfy normal distribution.

2.1 Description of the phenomena

Fig. 2 shows that before stimulation on head, whole-body and local thermal sensation are between slightly warm and warm. It can be seen that chest thermal sensation and back thermal sensation are similar to the whole-body sensation, and the extremities' vote of thermal sensation is low which is also mainly slightly warm. After head stimulation, whole-body and other body parts' thermal sensations are significantly changed, which indicates that the head has obvious effects on whole-body and other local parts' thermal sensations.

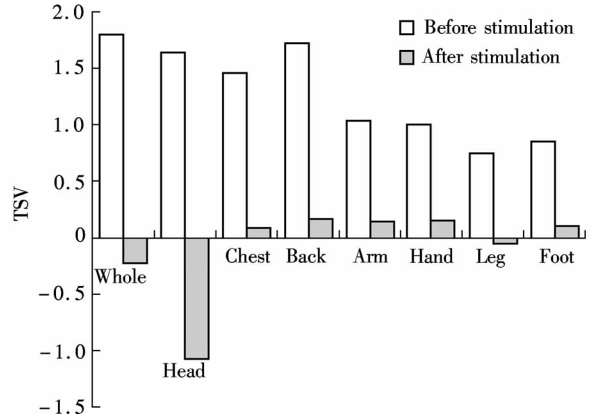

Fig. 2 Mean vote before and after stimulation on head

Fig. 3 shows that under uniform conditions, all body parts' thermal sensations are near the slightly warm, except for the foot which is neutral. After chest stimulation, every body part's vote decreases, which indicates that the chest also exerts a notable influence on other body parts. From the stimulation on the back, it is found that under uniform conditions, there is some difference between extremities and whole-body thermal sensations and there is a significant change in other body parts' thermal sensations. Figs. 4 and 5 show that after stimulation on the back and the arm, every body part's vote decreases while the most obvious is on the hand. It indicates that the arm has a great effect on the hand. It is shown in Fig. 6 that there is a notable change on the arm when the hand is stimulated while other parts have very little change. So the arm and the hand have a great mutual effect on each other. As shown in Fig. 7, with the stimulation on the leg, the whole-body, the foot and the trunk parts including the head, the chest and the back all have significant changes and there is little change on the arm and the hand. As shown in Fig. 8, the leg is influenced by foot thermal sensation to a certain extent. However, the changes in other parts are only from slightly warm to neutral and whole-body thermal sensation decreases a little.

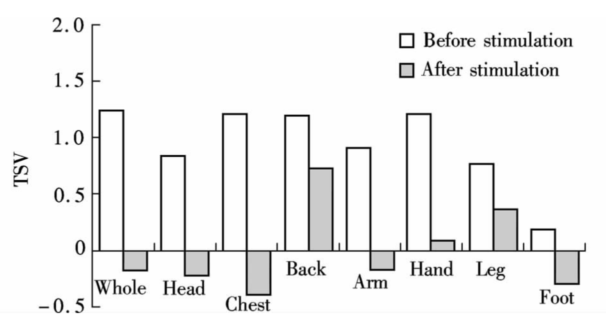

Fig. 3 Mean vote before and after stimulation on chest

Above all, under uniform conditions, different body parts have no conspicuous differences regarding thermal sensation. When the head, chest or back is stimulated, whole-body thermal sensation and other body parts' thermal sensations

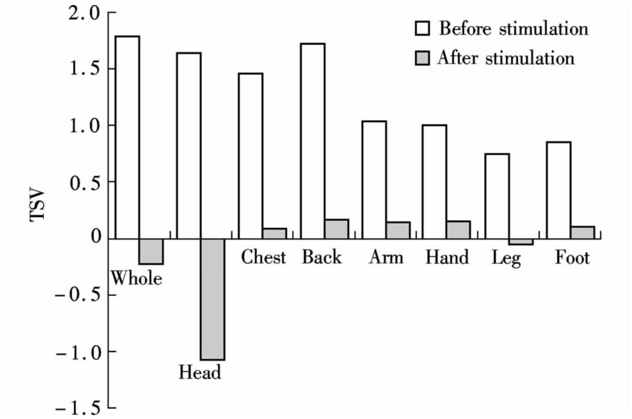

Fig. 4 Mean vote before and after stimulation on back

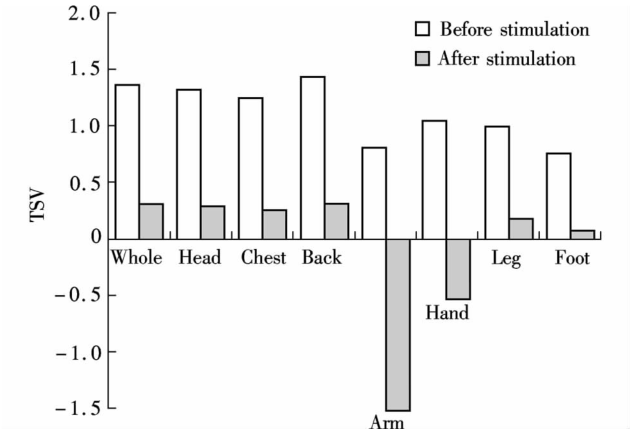

Fig. 5 Mean vote before and after stimulation on arm

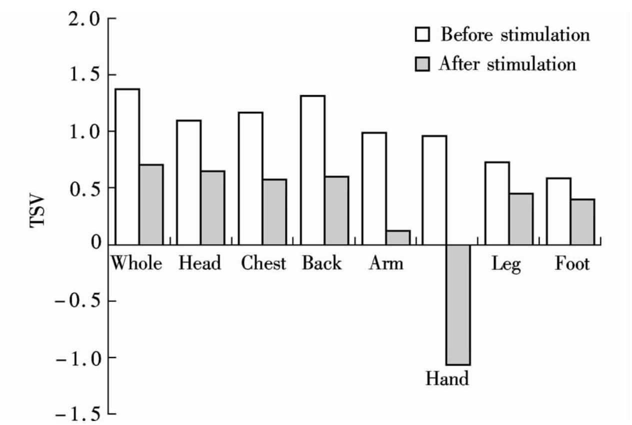

Fig. 6 Mean vote before and after stimulation on hand

will decrease to a large extent. When the leg is stimulated, there is some effect on whole-body thermal sensation, a notable influence on the foot and little effect on the others. The extremities have an obvious effect on neighboring body parts, however, it has not much effect on whole-body thermal sensation.

2.2 Multiple linear regression

The weighting factor is applied to evaluate the effects of local thermal sensation on whole-body thermal sensation in the present study. Multiple linear regression is widely used to obtain the weighting factor for each body part:

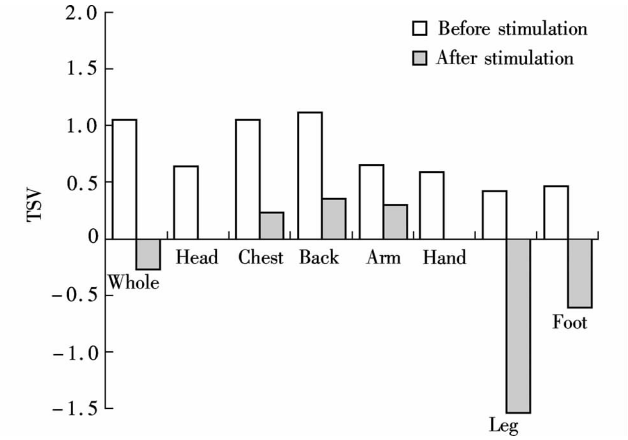

Fig. 7 Mean vote before and after stimulation on leg

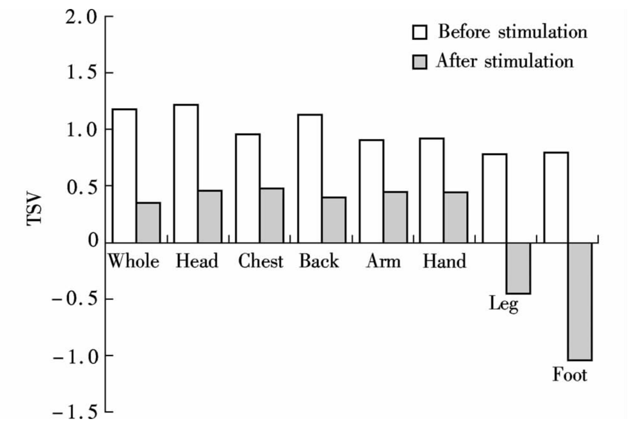

Fig. 8 Mean vote before and after stimulation on foot

$$TSV_O = \sum_{i=1}^{n} \partial_i TSV_i \quad (1)$$

where TSV_O is the whole-body thermal sensation; TSV_i is the local sensation for segment i; α_i is the weighting factor for segment i; n is the number of body parts.

From the above results and discussion, it is obvious that when some body part is stimulated, not only this part but also other parts which are not stimulated all have some changes in thermal sensation. Local thermal sensations among different body parts are correlated to some extent. In this paper, eigenvalue and ill-conditioned index are adopted to test multicollinearity [8]. For example, the results of head have a low eigenvalue of 0.002 and high ill-conditioned index of 49.883, which means that great multicollinearity exists for the head. Here, we use the principal component regression approach[9] to eliminate the multicollinearity. Through the analysis of principal component regression, the following results are obtained:

1) Local stimulation on extremity parts including arm, hand and foot only has a great effect on their neighbouring parts such as hand, arm and leg, which is consistent with the experimental phenomena.

2) Local stimulation on the trunk part can affect every body part and induce differences according to the body district, such as upper body, lower body, front body and back body.

3) The leg is an extremity and unique, so the rule is not the same. This may be because the leg has a large area and

there is a distinct blood stream in this body part. Thus, in some aspects it reflects the characteristics of the trunk.

2.3 Weighting factors of local thermal sensation

Tab. 4 shows the effects of every body part on the whole body under the conditions of different body part stimulations. The weighting factor reflects the proportions in the process of integrating the thermal sensation of a single body part with the whole body.

Tab. 4 Weighting factors of local thermal sensation with stimulation on different body parts

Stimulations	Head	Chest	Back	Arm	Hand	Leg	Foot
On head	0.20	0.15	0.16	0.13	0.13	0.13	0.10
On chest	0.13	0.13	0.14	0.14	0.16	0.17	0.13
On back	0.14	0.18	0.19	0.15	0.06	0.20	0.07
On arm	0.17	0.20	0.21	0.03	0.01	0.20	0.18
On hand	0.18	0.19	0.20	0.09	0.04	0.17	0.15
On leg	0.08	0.18	0.16	0.20	0.08	0.13	0.18
On foot	0.20	0.23	0.21	0.25	0.06	0.07	0.00

2.4 Predictive model of whole-body thermal sensation evaluation

The weighting coefficients in Tab. 4 are applicable when a single body part is stimulated, while actually there is little possibility for only one body part being stimulated under non-uniform environments. According to the above data, when the trunk is stimulated, the weighting factor of every body part is similar, which reflects the characteristics of the trunk. When an extremity is stimulated, the weighting factor of the part stimulated is low, which also indicates the principle of the extremity. However, the aim of this study is to obtain the weighting factors of body parts under stable non-uniform environments. Thus, the mean values of the above weighting factors for every body part are obtained as shown in Tab. 5.

Tab. 5 Weighting factors of local thermal sensation

Head	Chest	Back	Arm	Hand	Leg	Foot
0.16	0.18	0.18	0.14	0.08	0.15	0.12

In our research, the weighting factors of the local parts are independent of environmental parameters such as air temperature and air velocity under stable non-uniform environments. The environmental conditions are designed as neutral, cool, warm, etc. The weighting factors of the local parts reflect the inherent characteristics of the thermal responses of different body parts.

3 Discussion

The experimental results indicate that under stable non-uniform environments, the weighting factor of a single body part thermal sensation is independent of ambient temperature and air supply temperature and it is constant. Also, the weighting factor of the trunk is a little big. In the following, some significant achievements of other literature are compared with ours. Zhang[2] found that the weight increases with the difference between local thermal sensation and whole-body thermal sensation, especially for chest, back and coxa. While the weight in Ref. [2] is defined as the ratio of change of whole-body thermal sensation to that of local thermal sensation, when a single segment is stimulated. This definition is similar to the influencing factor involved in Zhang's research[10], which is different from our definition of the weighting factor. Here, the weighting factor is defined as the amount of a thermal sensation's changes in the whole-body thermal sensation when there is one unit variation of a single local thermal sensation, while other body parts' thermal sensations have no change. So our conclusions are different from Zhang's [2]. In Zhang's analysis[2], the stable data are combined with the transient ones, so different weights maybe reflect the effects of time. Zhang[10] obtained similar results to ours from the research on local exposure. The difference is that the stimulated body area is plotted into a large body part. The whole body is only divided into head, chest, back and lower body. It is thought that large areas of the body will not reflect some specific thermal response characteristics of extremities compared with the trunk. Furthermore, Zhang[10] explained the whole-body thermal sensation by using the thermal sensation's changes in the stimulated body part. But if the stimulated body part is not the same as that in the experiment, the whole-body thermal sensation prediction model cannot give a good prediction. In our study, the principal component regression approach is adopted, so the model does not need to rely on a single body part to explain whole-body thermal sensation. The weighting factor can be used when any body part is stimulated.

4 Conclusions

1) To eliminate the multicollinearity that exists in different body parts' thermal sensations, the principal component regression approach is adopted. The weighting factors of the local parts are independent of ambient temperature under warm and neutral conditions such as 26 ℃ and 30 ℃ under stable non-uniform environments in our study.

2) Local stimulation on an extremity part has a great effect on neighbouring parts such as the hand or the arm, but has little effect on other body parts. Local stimulation on the trunk part can affect every body part and induce differences according to the body district. Perhaps due to the large blood stream, the leg shows a special characteristic. To some extent, it shows the characteristics of the trunk.

3) It is found that under stable non-uniform environments, the weighting factor is constant and it is similar among different body parts, since in our research, the weighting factor has an integrated effect between different body parts after the processing of thermal exchange through blood fluxion.

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非均匀稳态环境局部热感觉对整体热感觉的影响

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摘要:为了揭示人体热反应机理、分析局部热感觉对整体热感觉的影响,通过对身体 7 个不同部位的冷刺激,开展了对人体主观热反应的实验研究(取 94 个样本),并建立了整体热感觉预测模型. 为消除各部位间存在的多重共线性影响,采用主成分回归方法获得不同部位刺激工况下的主成分. 然后通过多元线性回归和主成分分析,得到 7 个部位的权重系数. 最后,基于此权重系数建立整体热感觉的预测模型. 分析结果表明,躯干和肢体末端表现出不同的热反应特性,局部对整体热感觉的权重系数在物理意义上为一综合反应量,并且不同部位的权重系数相差不大.

关键词:局部热感觉;整体热感觉;非均匀环境;权重系数

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