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Evaluating effectiveness of four-parameter compound tactons for conveying urban navigation information

Jia Zhen Li Jianqing Xiao Yong

(School of Instrument Science and Engineering, Southeast University, Nanjing 210096, China)

Abstract: To guide pedestrians to navigate in a strange city and reduce the cognitive overload suffered when walking, thermal change direction, vibration stimulation direction, intensity variation and body location are employed to construct four-parameter compound tactons. They are mapped to four different types of navigation message: route attribute, intersection type, distance and heading direction. One psychological experiment was conducted. The derived confusion matrices were used to investigate recognition rates and information transfer for compound tactons, and non-parameter tests were employed to analyze the effect of each parameter on the number of correct responses. Experimental results show that the overall identification rate for four-parameter tactons is 88.72% by using different tactile parameters, and 19.64 icons can be identified reliably in all 32 tactile icons according to the information transfer value. Thermal changes can be an effective supplement to vibrotactile icons. This suggests that compound tactons will be a promising method of conveying complex information when navigating in a virtual or real urban environment.

Key words: tactile icons; navigation information; thermal display; vibrotactile feedback

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Nowadays, more frequent mobility activities are taking place in the modern and fast-paced society. One challenge for pedestrians is orientation in unknown spaces. However, it is difficult to navigate in a strange place. Even if there are fixed traffic signs, they cannot be seen when this place is very crowded, and are unavailable to blind people. Most navigation systems convey spatial information through the visual or audio channel, by which the information can nearly be accessed everywhere. However for the blind, they are neither hand-free nor an effective solution. Using visual and auditory channels can always distract the users' attention, and the information may be overwhelming due to sensory overload. According to Wickens' multiple resource theory (MRT) [1], allocating information from one overloaded sense modality to another modality can reduce workload. Therefore, the alternative tactile channel can be employed to convey navigation information.

There have been a number of studies on using vibrotactile feedback for navigation. Such tactile displays often took the form of vests or belts. The ActiveBelt invented by Tsukada et al.[2] was a waist belt equipped with eight vibrators, producing vibrotactile stimuli around the waist to "point" into a horizontal direction. With a similar waist belt, Pielot et al.[3] performed several studies on how pedestrians received navigation information in the form of vibrotactile feedback. Distance presentation can be more beneficial for spatial navigation, although direction information alone is sufficient to reach a turn. McDaniel et al.[4] presented intimate, personal, and social interpersonal distances to the blind by using tactile rhythms. Straub et al.[5] designed a vibrotactile waist belt to provide distance information for the pedestrians. By using a tactile torso display, Pielot et al.[6] presented the location and spatial distance of several people in a fast-paced 3D multiplayer game. Tactile icons ("tactons"), first proposed by Brewster et al.[7], are classified as one-element, compound, inherited, and transformational tactons. As structured vibrotactile messages, transformational tactons were later employed to provide navigation feedback. Lin et al.[8] proposed a pedestrian navigation system of conveying navigation information to the sighted user by using tactons. Different from transformational tactons, compound tactons are a sequence of two or more one-element tactile icons. However, few studies have used compound tactons to present non-visual information. In Ref. [9], we designed three-parameter compound tactons to encode urban navigation information, and found that the overall identification rate was rather high at 92.65% by using three vibrotactile parameters. This indicates that compound tactons are feasible to convey complex information.

In this paper, four-parameter tactons are employed to convey multi-dimensional navigation information in the form of thermal and vibrotactile stimuli. Based on the semi-infinite body model, the thermal response within the skin is investigated theoretically. One psychophysical experiment is performed to evaluate the effectiveness of

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Biographies: Jia Zhen (1987—), male, graduate; Li Jianqing (corresponding author), male, doctor, professor, ljq@seu.edu.cn.

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compound tactons for communicating navigation messages. Experimental results indicate that compound tactons have good performance in conveying non-visual information, and thermal changes can be an effective supplement to vibrotactile feedback.

1 Thermal Response within the Skin

The semi-infinite body model is a reasonable initial choice to model the contact between the finger and an object, and the model-based thermal display was proved to be effective in simulating different materials[10]. In previous research, thermal displays always served as a constant temperature source and maintained the interface temperature. However, the detection of thermal changes is dependent more on the stimulus change rate than the actual extent of the change itself (absolute temperature)[11]. Therefore, manipulating both thermal change rate and thermal intensity can perceptually create distinct stimuli. We propose that the thermal display can vary linearly from the initial skin temperature $T_{s,0}$, and then the interface temperature T_c is

$$T_c = T_s(0, t) = T_{s,0} + kt \qquad (1)$$

where k is a constant rate of thermal change, and t is the time. Based on the semi-infinite body model, the temperature profiles within the skin (for $x > 0$) can be calculated by

$$T_s(x, t) = T_{s,0} + 4kti^2\mathrm{erfc}\left(\frac{x}{2\sqrt{\alpha_s t}}\right) \qquad t \geqslant 0 \qquad (2)$$

where $T_{s,0}$ is the initial skin temperature; α_s is the thermal diffusivity of the skin. The heat flux conducted out of the skin during contact can be solved by

$$Q_s = \frac{2\lambda_s kt}{\sqrt{\pi\alpha_s t}} \qquad t \geqslant 0 \qquad (3)$$

where Q_s is the heat flux conducted out of the skin during contact; λ_s is the thermal conductivity of the skin. The heat flux changes within the skin will result in different thermal sensations in the human central nervous system. This significant difference may be in favor of identifying and discriminating various messages.

2 Experimental Setup and Icon Design

2.1 Tactile system construction

The experimental apparatus mainly consists of navigation information acquiring and display modules, a kernel control module, vibrotactile feedback module, and thermal display module, as well as the power supply. As shown in Fig. 1, the information acquiring unit is a NRF24L01 wireless module, which can receive the transmitted navigation information wirelessly, and send it to the kernel control module. An electronic compass is in charge of collecting the orientation information from the user himself. The kernel control module is a STM32VET6 controller, whose functions are decoding navigation information and encoding tactile language in the form of vibrotactile and thermal stimuli. The information display module is a TFT-LCD screen, displaying the received navigation information in real time. The vibrotactile feedback module includes the vibrotactile driving circuit and a waist belt, of which four vibrating motors are attached to the inside of the belt, and the driving circuit enables vibrators to produce vibrotactile stimulus. The thermal display module includes the thermal tactile driving circuit, the temperature sensor circuit and an armband. A Peltier with a heat sink is embedded into the armband. The sensor circuit measures the temperature of the Peltier surface and sends its values to the kernel control module in real time, and the driving circuit enables the Peltier to generate thermal stimulus. Besides, a backpack is chosen to carry the experimental apparatus. Fig. 2 presents the prototype of the wearable tactile navigation system.

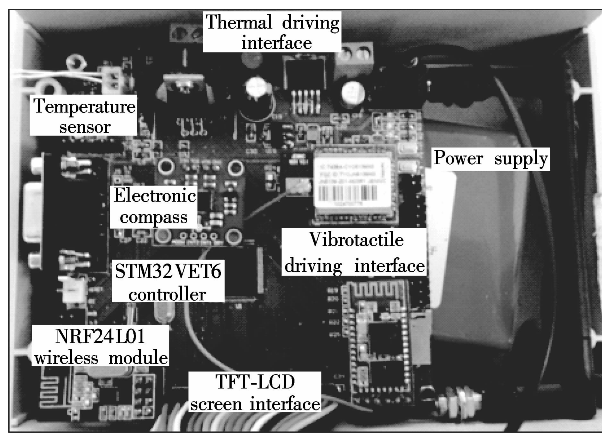

Fig. 1 Assembly photograph of the controller board

(a) (b)

Fig. 2 Prototype of the wearable tactile navigation system. (a) Front view; (b) Lateral view

2.2 Design of four-parameter tactons

Following the design principle of three-parameter tactons in Ref. [9], the four-parameter tactons were structured by adding another piece of information: the "Route Attribute" of a hypothetical navigation message, with the purpose to reduce navigation errors of walking in the urban environment. The route attribute can be either "deviation" or "on route". However, "destination" of the intersection type is removed in this case, as it appears only when reaching the destination in the real scenario. Therefore, the intersection type will be "crossing" or "landmark". As a result, this will generate 32 different message types. The extra thermal parameter chosen is the thermal change direction, as it is proved to be particularly salient[13]. This direction has two levels: warming and cooling. The chosen initial skin temperature is 30 ℃, a neutral skin temperature also used in Ref.[12], with stimuli warmed and cooled from this temperature. In previous works [13–14], 1 ℃/s was reported to be sufficient to produce detectable sensations in ideal conditions, and faster 3 ℃/s could create perceptually more distinct stimuli. The thermal change rate adopted in this paper for warming or cooling was 3 ℃/s, with the action time lasting 3 s. Warming is used to represent on-route messages, because warm stimuli are generally more preferred than cold one[15]. Cooling is then mapped to deviation messages. The mapping relationships between icon and message type are illustrated in Fig. 3. For the "distance" and "heading direction", their mappings between icon and message type keep unchanged [9].

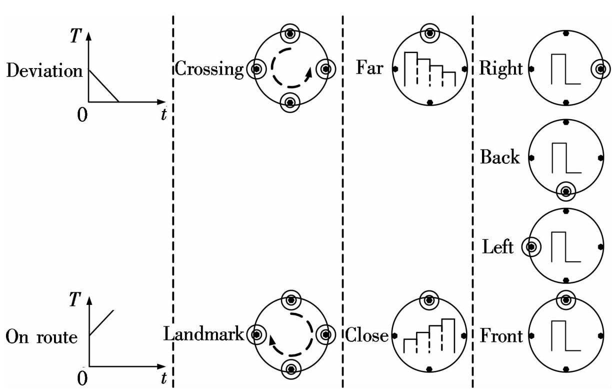

Fig. 3 Encoding categories of route attributes, intersection types, distances and heading directions

3 Evaluation of Four-Parameter Tactons

The experimental results in Ref.[9] indicated that the mean identification rate for three-parameter compound tactons is almost 10% higher than that for three-parameter transformational tactons[16], and subjects can identify almost 18 icons correctly of all 24 tactile icons. Therefore, we carried out an experiment to investigate subjects' ability to discriminate four-parameter compound thermal + vibrotactile icons.

3.1 Design and procedure

Sixteen normal healthy adults participated in this experiment (13 males and 3 females), aged between 23 and 29 years with an average age of 25.4. They were all students from Southeast University, and none of them had participated in the previous experiment in Ref. [9]. The subjects were first trained to recognize the four-parameter tactons prior to the experiment. The concept of icons was introduced to them, and the mapping relationships between vibrotactile parameters and attributes of the navigation messages were explained. Then they were allowed to sense each icon several times in 15 min, by clicking the buttons on the training interface. During this time, they had to associate the icons with their meanings. After becoming familiar with the icons, they took part in 32 tasks like those from the experiment itself as training in how to use the testing interface. Headphones were worn to block any noise from the vibrators.

All 32 icons were presented four times randomly, resulting in 128 trials for each subject in the experiment. Therefore, there were a total of 2 048 trials (i. e., 16 subjects × 2 thermal change directions × 2 stimulation directions × 2 intensity variations × 4 body locations × 4 presentations). In each trial, one icon was repeated two times with a one-second pause between repetitions. While the icon was being presented, the subjects had to identify all four attributes encoded in the icon, by selecting the corresponding radio buttons on the testing interface. They did not have to wait until the icon had been presented two times before responding if they had already decided. Then, they could submit their responses to carry out the next trial. All the experiment interfaces were built in a Visual C + + environment.

3.2 Results and discussion

Fig. 4 presents the confusion matrix of subjects' responses for the main session. The overall mean accuracy for four-parameter tactons is 88.72%. From the confusion matrix, the information transfer I_t from the stimulus set to the subject can be calculated by[17]

$$I_t = \sum_m \sum_n P_{mn} \log_2 \frac{P_{mn}}{P_m P_n} \tag{4}$$

where P_m is the probability of stimulus m; P_n is the probability of response n; P_{mn} is the joint probability of stimulus m and response n. According to the relation $N = 2^{I_t}$, The I_t can be considered to indicate the number N of categories perceived by the subject . After calculation, the I_t value is 4.30 bits, and 19.64 icons can, therefore, be distinguished reliably. Furthermore, the mean accuracy for the four thermal + vibrotactile parameters is 95.85% for thermal change direction, 97.61% for stimulation direction, 95.8% for intensity variation, and 98.63% for body location. The confusion matrix for each parameter is shown in Fig. 5.

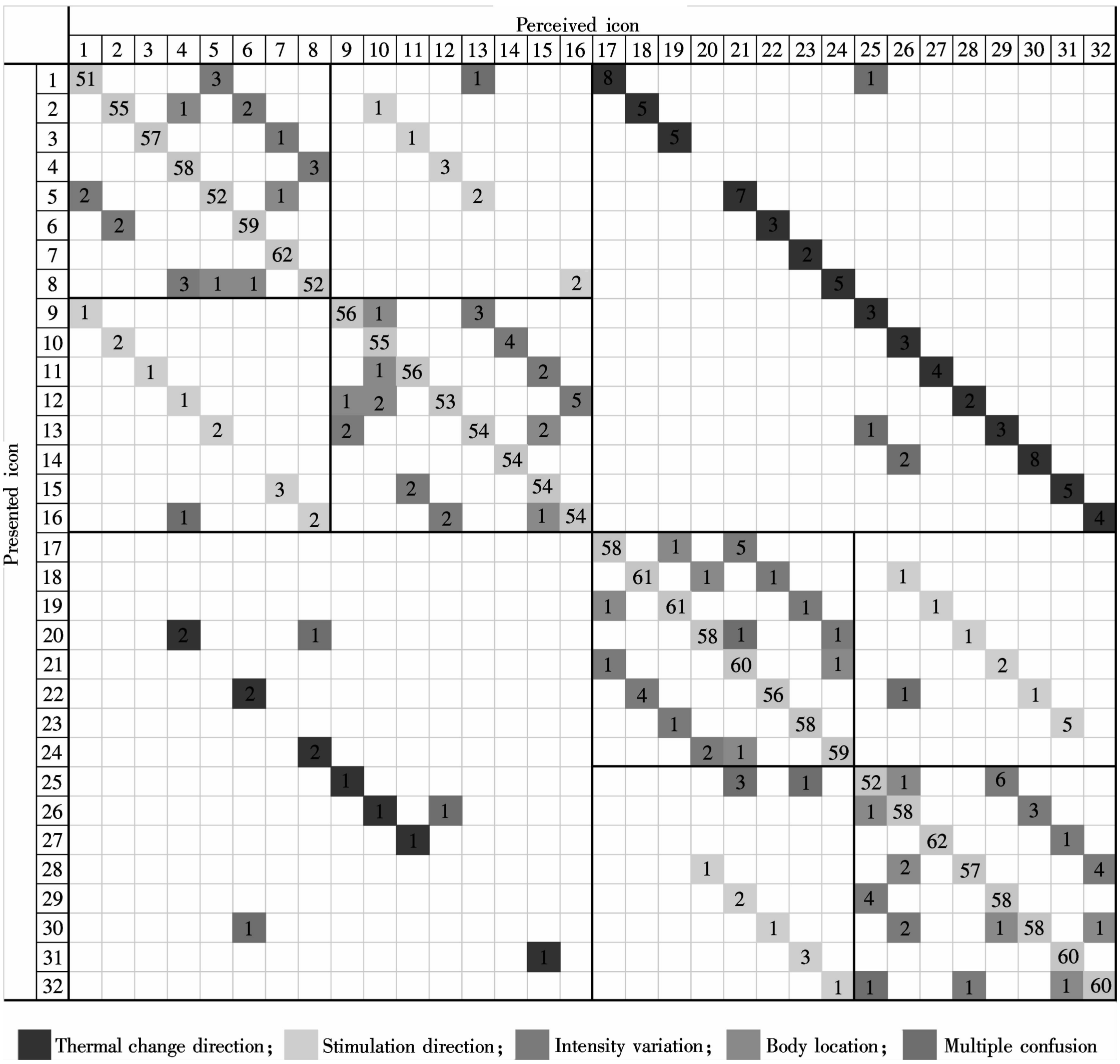

Fig. 4 Confusion matrix in the main session

Shapiro-Wilk tests showed that the data for four-parameter tactons violated the assumption of a normal distribution, so non-parametric tests were used, specifically Wilcoxon signed-rank tests for the effects of thermal change direction, stimulation direction, and intensity variation, and Friedman's test for the effect of body location. Post hoc pairwise comparisons following a significant Friedman's test were conducted using the Wilcoxon tests. Friedman's analysis of variance by ranks showed no effect of body location on the number of correct responses ($\chi^2(3)=4.178$, $p=0.194$), with means of 98.44%, 98.83%, 99.61% and 97.66% for the right, back, left and front, respectively. A Wilcoxon test showed that, the thermal change direction had a significant effect on the correct response counts, as subjects identified significantly more warm icons than cold icons ($Z=-3.189$, $p=0.001$). The mean recognition rates were 92.97% for cooling and 98.73% for warming. However, there were no significant main effects of either stimulation direction ($Z=-0.159$, $p=0.874$) or intensity variation ($Z=-0.361$, $p=0.718$) on the number of correct responses. Mean recognition rates for stimulation direction were 97.75% for clockwise (CW) and 97.46% for counter-clockwise (CCW), while mean recognition rates for intensity variation were 94.92% for decreasing and 96.68% for increasing. Fig. 6 shows the mean identification rates of all four-parameter tactile icon types.

Compared with three-parameter compound tactons in Ref. [9], four-parameter tactons have a lower mean identification rate at 88.72%, with 95.85% accuracy for thermal change direction, 97.61% accuracy for stimulation direction, 95.8% accuracy for intensity variation, and 98.63% accuracy for body location. Therefore, it appears that presenting thermal and vibrotactile stimuli sequentially does not significantly hinder interpretation of each other, and thermal changes may be an effective supplement to vibrotactile icons. When increasing the amount of information input, the amount of information transmitted for four-parameter tactons increases slightly, with 4.30 bits corresponding to 19.64 icons. In other words, of all 32 tactile icons, around 19 to 20 icons could be identified reliably. A non-parametric test indicated that, cold icons were significantly more difficult to identify than the warm icons. The reason is that the heat sink cannot efficiently dissipate the accumulated heat, which will distort subjects' judgment when the Peltier actually presents a cold stimulus.

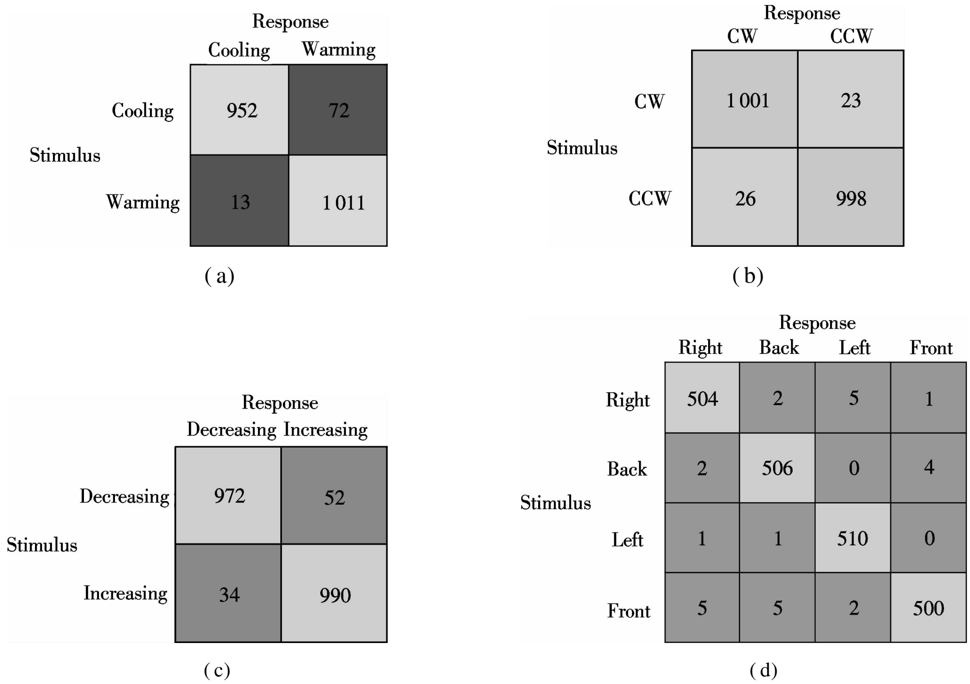

Fig. 5 Confusion matrix for each parameter. (a) Thermal change direction; (b) Stimulation direction; (c) Intensity variation; (d) Body location

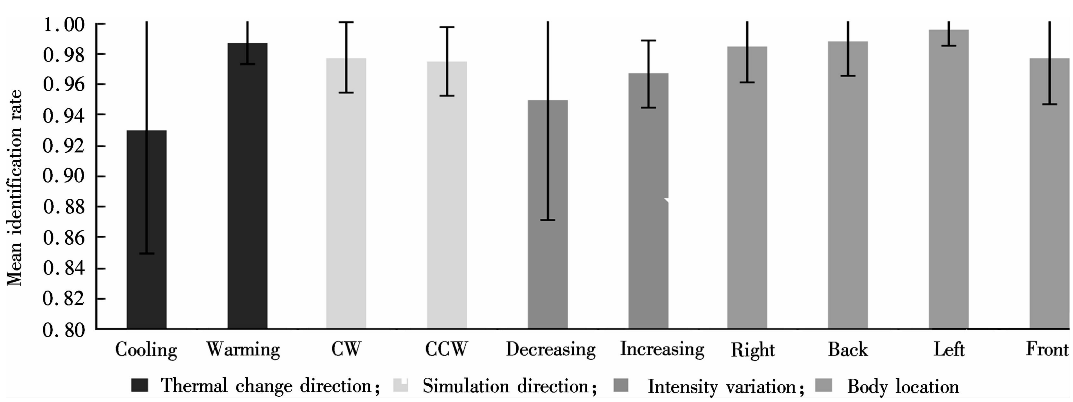

Fig. 6 Mean identification rates for all four icon types

4 Conclusion

This paper has conducted the evaluation of four-parameter thermal and vibrotactile icons, and the thermal response within the skin is studied on the basis of the typical semi-infinite body model. To evaluate the effectiveness of multi-dimensional compound tactons for navigation information displays, one psychophysical experiment is carried out, reporting that four-parameter tactons have a mean identification rate at 88.72% from the main confusion matrix, and about 19 to 20 icons can be identified reliably from all 32 tactile icons based on the information transfer value. It can be concluded that identifying four types of navigation information from the tactons is easy, and does not seem to produce confusion. A necessary next step is testing identification while the user is walking in a virtual or real urban environment. These initial results show compound tactons to be similarly effective in conveying multidimensional information as earcons and transformational tactons.

However, a pedestrian has more choices of orientation in the urban environment that need higher accuracy. Therefore, adding another four ordinal directions around the waist will be considered. To eliminate the significant differences between warm and cold stimuli, two Peltiers instead of one will be employed to cover a larger stimulus area[13]. Although the identification accuracy for compound tactons is distinctly high, the total duration required for perceiving sequential messages may be too long, making the information transfer rate very slow. Therefore, compound tactons can be combined with transformational tactons to convey navigation information.

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表达城市导航信息的四参数复合式触觉图标效能评估

贯 贞　李建清　肖 勇

(东南大学仪器科学与工程学院,南京 210096)

摘要:为了帮助行人在陌生的城市中寻路和降低行走时的认知负担,利用温度的变化方向、振动的刺激方向、强度变化以及身体位置 4 个触觉刺激参数构造了复合式的触觉图标,分别映射为 4 种不同的导航信息:路线属性、路口类型、距离和行进方向. 开展了一组心理物理学实验,利用模糊矩阵研究参与者对触觉图标的识别正确率和信息传输能力,并使用非参数检验分析了 4 个触觉参数对正确响应数量的影响. 实验结果表明:使用不同触觉参数构造出的复合式触觉图标,平均识别正确率可达到 88.72%;根据计算出的信息传输值,在所有的 32 个触觉图标中共有 19.64 个图标能够被可靠地辨识;温度变化可作为振动触觉图标的一种有效补充. 在以后的虚拟或真实城市环境中导航中,复合式触觉图标将是一种有潜力的传递这类复杂信息的方法.

关键词:触觉图标;导航信息;热显示;振动触觉反馈

中图分类号:TP391