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Development and Experimental Evaluation of a Thermal Display

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ABSTRACT

This work focuses on the development of a thermal display for creating a more convincing presentation of virtual objects and for studying the nature of human thermoperception. Current haptic feedback often fails to achieve a satisfying degree of immersion. Thereby, especially thermal displays might contribute to a sensation of presence but are often less considered. In order to identify the desired features of thermal displays the relevant physiological as well as psychophysical foundations are studied first. Based on these design considerations the chosen hardware and software approach is introduced and evaluated experimentally. Although compared to real-world benchmarks there are some technological constraints and the identification of simulated stimuli slightly lags reality, the set-up may be judged as valid and reliable: Both in simulation and in reality the same materials tended to be mistaken (r = 0.90). Besides, the perceived resolution of both the specific heat capacity (c = ± 0.05 cal /g °C) and the thermal conductivity (k ± 0.005 cal/cm s °C) are mostly high and thus, various material classes can be discriminated successfully.

Keywords: Thermoperception, Peltier Elements, Thermodynamic Feedback Model, Evaluation

1 INTRODUCTION

When reviewing the literature on haptic hardware it is apparent that a major part is dedicated to the development of kinaesthetic actuators while thermal feedback is paid far less attention. However, especially thermal actuators might be suited to create a more realistic perception of virtual objects and might have a similar effect on haptic actuators as colour has on visual displays [1].

Within this work the physiological and psychophysical specifications of human thermoreception are addressed in order to derive the desired features of thermal displays (Section 2). Adapted from these design considerations an appropriate hardware and software approach is presented which promises to enable immersive thermal feedback in remote environments and to study human thermoperception systematically (Section 3). For evaluation purposes an experimental study was carried out (Section 4). Finally, ongoing projects on display design and experimental efforts on the study of human thermoperception are addressed (Section 5).

2 DESIGN CONSIDERATIONS

Each modality is distinguished by several unique features with respect to how it processes sensory information. As the effectiveness of display design will depend on an understanding of these properties relevant aspects of thermoperception are to be regarded first [1, 2]:

a) Range: The ability to perceive temperature is due to two different kinds of nerve endings that are found in the epidermis and that are known as cold and warm receptors [3]. Between 30°C and 36 °C both types of receptors adapt quickly and stimulations are sensed as neither warm nor cold, but as neutral. This range of temperature is also referred to as the indifference zone. Beyond this threshold there is a constant hot or cold sensation which will pass into pain below 15 °C or above 48 °C, respectively. Thus, to avoid any nociception thermal displays should be operated within these parameters.

b) Rate of change: The thermal sensory system differs from other modalities such as vision or audition as the warm and cold fibres are less sensitive to absolute temperatures but are rather detectors of thermal change. For temperatures within the indifference zone humans are quite insensitive to slow changes, whereas temperature shifts that occur with at least 0.1 °C/s are detected more easily. While this rate of change constitutes a kind of lower physiological limit Jones and Berris [1] suggest that thermal displays should be able to realize a temporal transient resolution of at least 10 °C/s. However, this specification is motivated by the characteristics of thermoreception and by the operating range of their display but does not seem to be a required feature within this work. As the stimuli under consideration do not reveal large temperature differences cooling and warming rates of 2 °C/s seem to be sufficient here.

c) Resolution: Although the psychophysical relationship for sensing cooling and warming pulses differs and depends on various factors (e.g. site of stimulation, skin temperature) the differential perceptual threshold is in the order of 0.01 °C. Thus, a temperature sensor has to be chosen which operates at an appropriate resolution.

d) Spatial summation: Thermoreceptors register mainly the intensity and the duration of stimulation whereas poor spatial and temporal acuity is provided. Within a broad range the perceived intensity of the thermal stimulus is directly related to the spatial extent of stimulation. Thus, thermal thresholds may be maintained constant by increasing the area of skin that is stimulated while at the same time decreasing the intensity of the thermal stimulus. Considering this capacity for spatial summation the optimal array of thermal actuators, their dimension as well as their alignment on the fingers and the palm has to be figured out empirically. However, it is unlikely that more than 10 sites per hand may be resolved independently.

When developing displays it must be kept in mind that human thermoreceptors do not operate as thermometers as it is the rate, the duration, and the extent of stimulation that has crucial impacts on how a thermal stimulus is perceived.

3 THERMAL FEEDBACK

Based on these design considerations a thermal display was developed that provides a resolution of 0.01 °C at a temperature change of 2 °C/s. To avoid nociception the operating range was limited to 33 °C (15 – 48 °C). The actuators are small enough to be placed on the phalanx and may be integrated into a commercially available data glove

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(see 3.1). In order to display temperatures as they would occur during direct physical contact an appropriate feedback algorithm was chosen (see 3.2).

3.1 Hardware

Most often thermal displays consist of temperature sensors, heat sinks, and thermoelectric elements that use the Peltier effect [e.g. 4, 5, 6, 7, 8, 9, 10]. This thermoelectric effect is a direct conversion of electric voltage to temperature differentials. It occurs when a current is passed through a circuit containing semiconductors of different conductivity types. As a result of the current flow one junction cools off while the other heats up. As this effect is reversible Peltier elements can be used for displaying both warm and cold thermal stimuli: when changing the direction of current the former cool side will warm up while the former warm side will cool down. The temperature at one side is referred to as display temperature, whereas the other side is called reference temperature.

When displaying cold temperatures over a long time a constant warming of the reference side is to be observed. As the here applied Peltier elements are too small to dissipate the occurring heat to the environment an unintended warming of the display side cannot be avoided either. Thus, to ensure that the temperature at the reference side does not reach a maximum (i.e. stays at ambient temperature level) a commercially available PC water cooling circuit was integrated which consists of an expansion tank, a pump, a radiator, and three fans [11] (figure 1 top).

Within this set-up the phalanx of each finger is actuated by a miniature Peltier element (8 x 8 x 3 mm^3) that is attached to a thin aluminium box [12]. These boxes are designed as heat exchangers between the Peltier element and the water circuit. Besides, in each box a temperature sensor (PT-100 element) is integrated for considering interferences caused by blood circulation and metabolism (see 3.2). Due to the high thermal conductivity of aluminium an optimal thermal contact between phalanx and display is realized.

For providing thermal feedback while exploring virtual objects a low-cost glove like device (P5-glove) was adapted [13]. Therefore, the control unit of the glove, which is integrated in a plastic shell on the back of the hand, was enhanced by a distribution system for the water cooling circuit. The distributor is connected to the phalanx actuators by water hoses that are also guided at the back of the hand. Besides, the position and bending sensors of the device were sewed in a stabile cotton glove to provide an easy-to-use system.

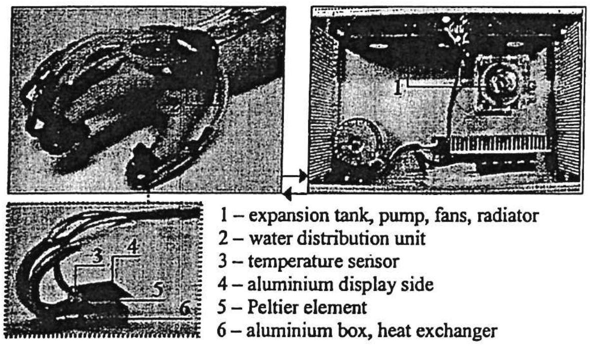

Figure 1: Skeleton of a thermally actuated data glove (top) with an integrated Peltier display (bottom).

3.2 Software

For developing thermal feedback models it is to be kept in mind that it is not the absolute temperature but the dynamic change of temperature that is encoded by the thermoreceptors (see 2b). Thereby, especially the thermal conductivity and the specific heat capacity of materials are relevant for object identification [14, 15]. Whereas the first term refers to the ability of a material to conduct heat, the second one characterizes its ability to store heat [16].

Thus, when displaying temperatures as they would occur during direct physical contact the occurring *heat flux* has to be modelled. The heat flux describes the energy that is flowing through a certain surface per time. This energy can be transported by means of conduction or convection: Heat conduction takes place when two objects (e.g. skin and material) are in direct contact with each other and the temperature of one object is higher than the temperature of the other one. As the temperature tends to equalize the heat conduction consists of a transfer of kinetic energy from the warmer object to the cooler one. Heat convection occurs when the motion of a fluid (e.g. blood) carries energy from a warmer region to a cooler one [17, 18]. For simulating this heat flux various approaches have been suggested that differ in their complexity:

a) The thermal feedback model introduced by [8] considers thermal exchange due to conduction solely. Both the skin and the palpated material are regarded as two semi-infinite bodies that are in contact. Thus, the model is only suited to display short, transient interactions.

b) The approach chosen by [7] is more complex as the thermal transfer is modelled by two sub-systems: Besides, the conduction exchanges between skin and material, body-inherent convection processes due to thermoregulation are taken into account, too.

c) By referring to the work of Bergamasco and colleagues [19] a more detailed model was proposed by Kron [9]. Within this work conduction and convection processes are distinguished. Furthermore, the skin is not regarded as homogeneous but as consisting of three layers of tissue that differ in terms of heat flux: epidermis (n = 1), dermis (n = 2), and endodermis (n = 3).

The thermal balance between two adjacent layers is described by ordinary differential equations. Thereby, the thermal properties, such as the thermal conductivity k_n [cal / cm s °C], the specific heat capacity, c_n [cal / g °C], the density, ρ_n [g / cm^3] or the thickness of a layer, Δx_n [cm], may be derived from literature [20, 21].

The heatflow $\hat{\Phi}$ between layer n+1 and n can be described by equation (1), whereas K accounts for different thermal conductivities each layer and A is the hypothetical contact area between the layers:

$$\hat{\phi}_{(n+1,n)} = K_{(n+1,n)} A (T_{n+1} - T_n) \qquad (1)$$

$$K_{(n+1,n)} = \frac{2}{\frac{\Delta x_{n+1}}{k_{n+1}} + \frac{\Delta x_n}{k_n}} \qquad A = A_1 = A_2 = A_3$$

The time continuous temperature characteristic of the epidermis, T_1, is given by equation (2). Herein, the heat flux per unit area to the environment, $\hat{\Phi}_{env}$, is considered by a negative sign, whereas the corresponding heat flux from the dermis to the epidermis is expressed by a positive sign.

$$\dot{T} = \frac{dT_1}{dt} = \frac{-\hat{\phi}_{env} + \hat{\phi}_{(2,1)}}{\Delta x_1 \rho_1 c_1} = \frac{-\hat{\phi}_{env} + \frac{K_{(2,1)}(T_2 - T_1)}{\Delta x_{(2,1)}}}{\Delta x_1 \rho_1 c_1} \quad (2)$$

For modelling $\hat{\Phi}_{env}$ two different situations are to be distinguished (3): When palpating an *object* the heat transfer is described by conduction processes (equation 3 left). Whereas convection occurs when the finger is in the *air* and no object is touched (equation 3 right):

$$\hat{\phi}_{env} = \frac{K_{(1,env)}(T_1 - T_{env})}{\Delta x_{(1,env)}} \qquad \hat{\phi}_{env} = \alpha_{env}(T_1 - T_{env}) \quad (3)$$

Under both conditions the material properties of the environment, such as the temperature of the environmental medium, T_{env}, have to be considered. Besides, the conduction process is determined by the thickness, Δx_{env}, and the thermal conductivity, k_{env}, of the touched material. In contrast to this the heat transfer coefficient, α_{env}, is relevant for describing the convection process.

In analogy to (2) the dynamic temperature distribution within the dermis, $\dot{T}_2$, is obtained by (4):

$$\dot{T}_2 = \frac{dT_2}{dt} = \frac{\frac{-K_{(2,1)}(T_2 - T_1)}{\Delta x_{(2,1)}} + \frac{K_{(3,2)}(T_3 - T_2)}{\Delta x_{(3,2)}}}{\Delta x_2 \rho_2 c_2} \quad (4)$$

For modelling the temperature characteristics of the endodermis, T_3, heat flow due to metabolic processes, $\hat{\Phi}_m$, and blood circulation, $\hat{\Phi}_b$, has to be regarded (5). Thereby, the arterial blood temperature is assumed to be constant, T_{art} = 36.8 °C [17, 22].

$$\dot{T}_3 = \frac{dT_3}{dt} = \frac{\frac{-K_{(3,2)}(T_3 - T_2)}{\Delta x_{(3,2)}} + \hat{\phi}_m + \hat{\phi}_b}{\Delta x_3 \rho_3 c_3} \quad (5)$$

The equations (2), (4), and (5) may be summarized as a system of first-order linear differential equations with the system matrix A_t and the input matrix B_t. For a sampling rate h the continuous temperature distribution at a certain point in time p can be expressed by (6):

$$\begin{pmatrix} T_{1,p} - T_{1,p-1} \\ T_{2,p} - T_{2,p-1} \\ T_{3,p} - T_{3,p-1} \end{pmatrix} = hA_t \begin{pmatrix} T_{1,p} \\ T_{2,p} \\ T_{3,p} \end{pmatrix} + B_t \begin{pmatrix} T_{env,p} \\ T_{art,p} \\ \hat{\Phi}_{m,p} \end{pmatrix} \quad (6)$$

By solving equation (6) the time discrete temperature distribution in each of the three layers can be derived. As the thermoreceptors are located in the epidermis, the set point temperature is provided by T_1.

Actually, the epidermis is not in contact with an object but with a Peltier element. For taking into account the thermal contact between finger and display a second 3-layer tissue model is set up (7). To obtain the display temperature, $T^s_{d,p}$, the equation system is to be solved by equating the actual value, $\tilde{T}_1$, to the target value, T_1.

$$\begin{pmatrix} \tilde{T}_{1,p} - \tilde{T}_{1,p-1} \\ \tilde{T}_{2,p} - \tilde{T}_{2,p-1} \\ \tilde{T}_{3,p} - \tilde{T}_{3,p-1} \end{pmatrix} = h\tilde{A}_t \begin{pmatrix} \tilde{T}_{1,p} \\ \tilde{T}_{2,p} \\ \tilde{T}_{3,p} \end{pmatrix} + \tilde{B}_t \begin{pmatrix} T^s_{d,p} \\ T_{art,p} \\ \hat{\Phi}_{m,p} \end{pmatrix} \quad (7)$$

The thermodynamic model as introduced by Kron [9] was implemented in Matlab / Simulink. An optimal fit to the model was achieved by a PID-controller. Besides, to avoid measurement noise that is caused by the temperature sensor a low pass filter was integrated (figure 2).

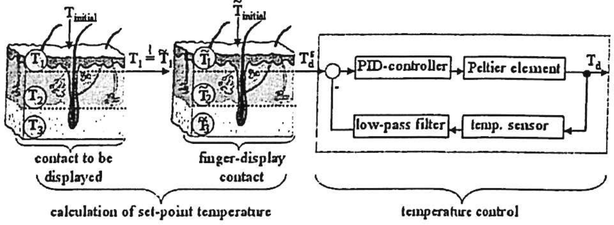

Figure 2: Information flow of the thermodynamic model [9].

4 EXPERIMENTAL EVALUATION

For evaluating the set-up both objective (4.1) and subjective (4.2) criteria are considered. The experimental stimuli are chosen to represent various material classes that are relevant in virtual interactions: aluminium, steel, stone, wood, and hard rubber (table 1).

Though the thermal properties of these materials differ they do not cover the value range equidistantly which may be more important in studies focusing on human thermoperception (see Section 5). To avoid any interference only stimuli with little texture and stiffness information were taken into account and all stimuli were of equal size.

Table 1: Material properties (thermal conductivity k; specific heat capacity c; density ρ) of experimental stimuli [23].

material	k [cal / cm s °C]	c [cal / g °C]	ρ [g / cm³]
aluminium	0.52600	0.215	2.70
steel	0.11000	0.120	7.85
stone	0.00660	0.194	2.70
wood	0.00033	0.598	0.60
rubber	0.00032	0.387	0.99

4.1 Objective Assessment

For each material the dynamic temperature distributions were recorded within both real and simulated contact situations. Although this comparison is useful it should be mentioned that only similar and not identical results are to be expected:

First, within the thermal feedback model optimal conditions (e.g. homogeneous density within objects) are assumed. In contrast to this, real-world stimuli may not meet these strict criteria completely.

Second, the simulation is based on thermal parameters that are reported in literature [24]. In doing so a nominal congruence between real and simulated materials may be achieved but minor discrepancies concerning the thermal conductivity or the specific heat capacity cannot be avoided. Such, for instance, several hundred types of stainless steel may be distinguished [23].

Keeping these constraints in mind the following experimental procedure was chosen: A temperature sensor was attached on the index finger and each material was either touched or simulated for 90 seconds, respectively. To obtain representative results each assessment was repeated three times and the average temperature curves were evaluated (figure 3). The mean ambient temperature accounted for 23 °C. Due to inter-individual variations the initial finger temperature was not set to a specific value but measured for each subject at the beginning and during the experiment; data sets that differ by > 1 °C were discarded.

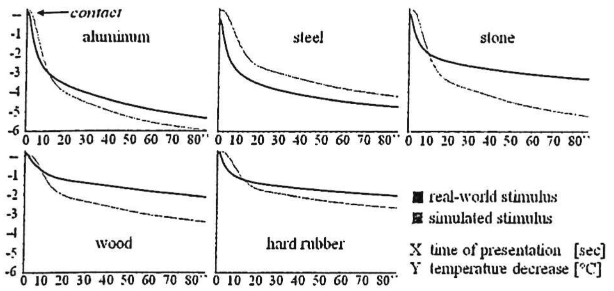

Figure 3: Mean temperature curves for simulated and real-world contact situations as recorded at the index finger of one subject within three repeated measurements.

As already mentioned before this comparison was not carried out to demonstrate equivalence of simulated and real-world contact situations but focuses rather on a qualitative interpretation: With the exception of steel all simulated curves are characterized by a slower initial temperature decrease; after about ten seconds the simulations start to become colder and finally reach a deeper endpoint temperature than the real-world contacts. The apparent initial delay is probably due to constraints concerning the cooling capacity of the applied miniature Peltier elements and may not be overcome. However, the further cooling down might be caused by the inertia of the temperature control and will be improved within future work.

The deviating behaviour of the steel-simulation can be explained by two reasons: First, within the simulated trials a marginally higher initial finger temperature could not have been controlled. Second and more important, the simulation is probably based on slightly different thermal properties than those revealed by the real-world counterpart. Just the same the simulations for wood and stone reveal an apparent colder endpoint that is due to a steeper initial temperature gradient. This observation, too, is likely to be caused by varying material properties for both conditions. Although these aspects may be taken into account by actually measuring the thermal properties of the real-world objects it is of little practical relevance for designing thermal feedback in virtual environments. Here, material classes with characteristic thermal signatures rather than specific objects are to be displayed. Nevertheless, what is interesting is the apparent limitation of the initial cooling capacity as well as a possible inertia of the system.

4.2 Subjective Assessment

To explore whether these technological constraints challenge valid simulations of materials, it is the perceived quality of thermal feedback that is crucial. For this reason all objects were first shown and afterwards presented to 15 blindfolded participants by thermal feedback. The experiment was carried out as a within-subject design so that one half of the subjects experienced at first the real-world and then the simulated condition whereas the reverse order was chosen for the other half of participants. Besides, sequential effects were balanced by varying the materials systematically. After 30 seconds of presentation the participants were asked to identify the material. By choosing a sequential identification procedure the experiment focuses on the recognition of material classes rather than on a pair comparison of real-world and simulated stimuli. Further on, it is to be mentioned that the presentation was limited to the index finger for facilitating standardized experimental conditions. To avoid any additional texture, stiffness or friction feedback the real-world stimuli were not palpated by lateral exploration but by static touch without exerting pressure.

Within the experiment questions concerning the validity, the homogeneity, and the perceived resolution of the display were addressed:

a) Validity: To obtain an upper limit for the ability of human thermal object identification the mean classification probabilities of the real objects were regarded first. Here, 66% of all real-world stimuli were classified correctly, whereas identification by guessing accounted for 20% (1:5).

Referring to this baseline the perceived quality of simulation was considered next. An appropriate index is provided by the probability ratio of simulated to real classifications (8):

$$\frac{\text{probability}_{\text{correct identification of simulated material}}}{\text{probability}_{\text{correct identification of real material}}} \quad (8)$$

Thereby, no difference between simulated and real-world classifications would be indicated by a ratio of one. For correct classifications (bold in table 2) a ratio larger than one is to be interpreted as an advantage of the simulation over the reality; the reverse relationship holds for false classifications (italic in table 2).

Table 2: Mean probability ratios of simulated to real classifications; missing values are due to zero-probabilities.

▾ identified ▸ presented	aluminium	steel	stone	wood	rubber
aluminium	**1.01**	*1.25*	*3.21*	–	–
steel	*0.82*	**0.67**	–	–	–
stone	–	*2.14*	**0.54**	*4.61*	*1.07*
wood	–	–	*2.14*	**0.73**	*1.07*
rubber	–	–	*1.07*	*0.38*	**0.97**

In average simulated materials were classified only 0.78 times as well as their real-world counterparts whereas false classifications occurred 1.78 times more often.

A further interesting indicator for the validity of the simulation is provided by taking a closer look at the kind of mistakes. To assess whether the same materials were mistaken under real and simulated trials a correlational analysis was carried out. The correlational coefficient ($r = 0.90$) is very high and thus, it can be concluded that under both conditions the same stimuli tended to be mixed up.

To sum up, the human ability to identify objects solely by thermal feedback is poorly developed and was limited to two-thirds of the experimental stimuli. Although the identification rates decreased slightly further by simulating temperature feedback the applied thermal feedback model proves to be valid as the kind of mistakes are very similar to real-world object identification.

b) Homogeneity: Referring to the results of Ho and Jones [8] differences in the probability of a correct classification were expected for the various materials. This issue can be addressed by a χ^2-test. The analysis is based on the null hypothesis that the correct classifications are independent of the simulated materials and considers the frequencies of true and false classifications (table 3). The test statistic accounts for $\chi^2(4) = 4.10$, whereas the corresponding 95%-quantile of the central χ^2-distribution is $\chi^2(0.95;4) = 9.49$. Thus, the null hypothesis must be maintained and it can be concluded that there are no systematic differences concerning the identification probabilities of various materials.

Table 3: Conditional frequencies of true and false classifications for simulations.

	true classifications	false classifications
aluminium	54 %	46 %
steel	36 %	64 %
stone	43 %	57 %
wood	71 %	29 %
rubber	54 %	46 %

c) Discrimination: So far the analysis has only distinguished between true and false classifications. Further interesting insights are gained when taking into account the metric differences between the identified and the actually presented material both for the specific heat capacity $\Delta(c_{identified} - c_{presented})$ and the thermal conductivity $\Delta(k_{identified} - k_{presented})$. The corresponding probabilities of classification are summarized in figure 4.

For the specific heat capacity 27 % of all mistakes occurred in an interval of c ± 0.05 [cal / g °C], whereas for the thermal conductivity 44 % of all mistakes were located within an interval of k ± 0.005 [cal / cm s °C]. For both parameters the mistakes decreased with the increasing of the interval.

Thus, it may be concluded that the thermal display is suited to display various material classes at a high resolution. Actually, it is to be mentioned that the intervals may become even smaller when taking into account other experimental stimuli. Though analyzing the curvatures of the histograms would give evidence on just-noticeable differences this issue is not addressed within this study but will be subject of further research (see Section 5).

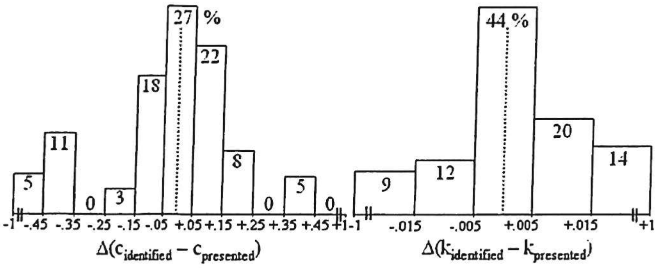

Figure 4: Mean classification probabilities for materials differing in specific heat capacity (left ordinate) and thermal conductivity (right ordinate) related to the degree of mistakes (abscissa); correct classifications are located at the zero-point (dashed line), whereas false classifications are different from zero.

5 CONCLUSION

Within this work the hard and software development of a thermally actuated data glove is presented that is based on physiological as well as psychophysical insights of human thermoreception. Besides, an experimental study was carried out to evaluate the validity and the reliability of this approach. When comparing the dynamic temperature distributions of real-world and simulated contact situations two issues become apparent: The initial cooling capacity of the applied miniature Peltier elements and the inertia of the system remain behind reality. Nevertheless, it is the perceived quality of the thermal feedback that is decisive: Although the identification rates of simulated materials lag behind real-world benchmarks almost no arbitrary mistakes occurred and both in reality and in simulation the same materials tended to be mixed up. Besides, the quality of simulation does not vary for different materials and the display enables a fine discrimination of thermal properties. Thus, it is to be concluded that material classes that are relevant for virtual interactions can be displayed appropriately with the presented set-up.

For improving the display further the identified technological constraints (e.g. temperature control) are subject of current research. Besides, when taking into account that only two-thirds of the real-world objects were classified by thermal feedback correctly it is reasonable to enhance the display by a vibro-tactile actuator. In an ongoing project a low-cost miniaturized DC-motor (as usually used in cell phones for vibration alarm) is integrated in our data glove to simulate surface roughness and an appropriate feedback model is elaborated.

As there is still insufficient knowledge for developing thermal displays systematically the following questions are addressed in present experiments:

a) Spatial summation: Within the experimental evaluation presented in section 4 the stimulation was limited to the index finger. Due to the human ability of spatial summation it remains open how many Peltier elements can be processed independently and should thus, be integrated in a data glove. For this reason the appropriate number, size, form (e.g. rectangle, square, circle) and alignment (e.g. palm, phalanx) of thermal actuators is subject of current research. First interesting insights were gained by asking the participants to make a drawing of how they have felt their hand had been stimulated.

b) Sensory fusion: The main intent of this study was to evaluate the set-up according to its ability enabling immersive feedback in virtual environments. For this reason experimental stimuli were chosen which represent various material classes. To make more general contributions to human thermoperception another experimental study is carried out at present. The stimuli chosen here span the value range of thermal conductivity and specific heat capacity equidistantly. By regarding the stimuli as tuple a conjoint measurement approach is taken to explore the sensory integration process of thermal conductivity and specific heat capacity to a consistent thermal sensation.

c) Intra-modal interaction: The availability of vibro-tactile actuators offers the possibility of examining intra-modal interactions. Such, for instance, it could be shown that the perception of roughness is correlated to the skin temperature to a certain degree [24, 25]. As these interaction effects would provide potential benefits in terms of display design they are also subject of further research.

To conclude, the display which is presented in this work provides a valid instrument for being applied in virtual environments and for addressing more general questions related to human thermoperception.

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REFERENCES

[1] L. A. Jones and M. Berris. The Psychophysics of Temperature Perception and Thermal-Interface Design, *Proc. of the 10th Symp. on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, pages 137–142, 2002.

[2] N. Birbaumer and R. F. Schmidt. *Biologische Psychologie*. Berlin, Springer, 2003.

[3] S. Nomoto, M. Shibata, M. Iriki and W. Riedel. Role of body afferent pathways of heat and cold in body temperature regulation, *Int. Journal of Biometeorology, 49* (2), pages 67-85, 2004.

[4] M. Zerkus, B. Becker, J. Ward and L. Halvorsen. Temperature Sensing in Virtual Reality and Telerobotics, *Virtual Reality Systems, 1* (2), pages 88-90, 1993.

[5] D. G. Caldwell, S. Lawther and A. Wardle. Tactile Perception and its Application to the Design of Multi-modal Cutaneous Feedback Systems, IEEE Int. Conf. on Robotis and Automation, Minneapolis, Minnesota, pages 3215-3221, 2006.

[6] J. Dionisio. Virtual Hell: A Trip Through the Flames, *IEEE Computer Graphics and Applications, 17* (3), pages 11-14, 1997.

[7] M. Benali Khoudja, A. Hafez and A. Kheddar. Tactile Interfaces. A State of the Art Survey, *35th Int. Symp. on Robotics, available at: www-list.cea.fr/fr/publications/docs/si/realite_virtuelle/gb/isr_2004 _ khoudja.pdf* [2006/05/31], 2004.

[8] H. Ho and L. A. Jones. Material Identification Using Real and Simulated Thermal Cues, *Proc. of the 26th Ann. Int. Conf. of the IEEE EMBS*, pages 2462–2465, 2004.

[9] A. Kron. *Beiträge zur bimanuellen und mehr-fingrigen haptischen Informationsvermittlung in Telepräsenzsystemen. Fortschritt-Berichte Nr. 1062*. Düsseldorf, VDI-Verlag, 2005.

[10] A. Drif, J. Citerin and A. Kheddar. Thermal Bilateral Coupling in Teleoperators., *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 2818–2823, 2005.

[11] Alphacool GmbH, *available at: www.alphacool.de* [2006/05/31].

[12] UweElectronic GmbH, *available at: www.uweelectronic.de* [2006/05/31].

[13] Alliance Distributors Holding Inc, *available at: www.essentialreality.com* [2006/05/31].

[14] A. Yamamoto, B. Cros, H. Hashimoto and T. Higuchi. Control of thermal tactile display based on prediction of contact temperature, *IEEE Int. Conf. on Robotics and Automation, Vol. 2*, pages 1536–1541, 2004.

[15] H.-H., Ho and L. A. Jones. Thermal Model for Hand-Object Interactions. *Symp. on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, pages 461–467, 2006.

[16] W. D. Callister. *Fundaments of Materials Science and Engineering: An Integrated Approach, 2nd ed.*, New York, John Wiley & Sons, 2004.

[17] F. P. Incropera and D. P. deWitt. *Fundaments of Heat and Mass Transfer, 5th ed.*, New York, John Wiley & Sons, 2004.

[18] J. Lienhard. *A Heat Transfer Book*, Cambridge, Phlogiston Press, 2003.

[19] M. Bergamasco, A. A. Alessi and M. Calcara. Thermal Feedback in Virtual Environments, *Presence: Teleoperators and Virtual Environments, 6* (6), pages 617-629, 1997.

[20] M. Lipkin and J. D. Hardy. Measurement of Some Thermal Properties of Human Tissue, *Journal of Applied Physiology, 7*, pages 212-217, 1954.

[21] R. Skalar and S. Chien. *Handbook of Bioengineering*, New York, McGraw-Hill, 1987.

[22] G. Bruggencate. Allgemeine Physiologie sensorischer Systeme. In P. Deetjen and E. J. Speckmann (eds.), *Physiologie*, München, Urban & Fischer, pages 42-87, 1999.

[23] MatWeb, material property data, available at: www.matweb.com/search/SearchProperty.asp [2006/05/31].

[24] B. G. Green, Temperature perception and nociception, *Journal of Neurobiology*, 61, pages 13–29, 2004.

[25] B. G. Green, S. J. Lederman and S. C. Stevens. The effect of skin temperature on the perception of roughness, *Sensory Processes*, 3, pages 327–333, 1981.