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Evaluating Contact Thermal Comfort for Consumer Mobile Devices

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INTRODUCTION

In recent years, consumer mobile devices have become increasingly diverse, and their power consumption has also risen markedly alongside improvements in performance. Current thermal design often prioritizes rapid heat dissipation in order to sustain higher performance output. In smartphones, for example, the enclosure has evolved from glass back covers combined with metal middle frames to fully metallic bodies. As heat is conducted away from devices more efficiently, users' perception of device heating is correspondingly intensified, with direct consequences for thermal experience. It is important to incorporate user thermal comfort into the thermal design of mobile devices.

At present, the upper limit for acceptable device heating is defined mainly

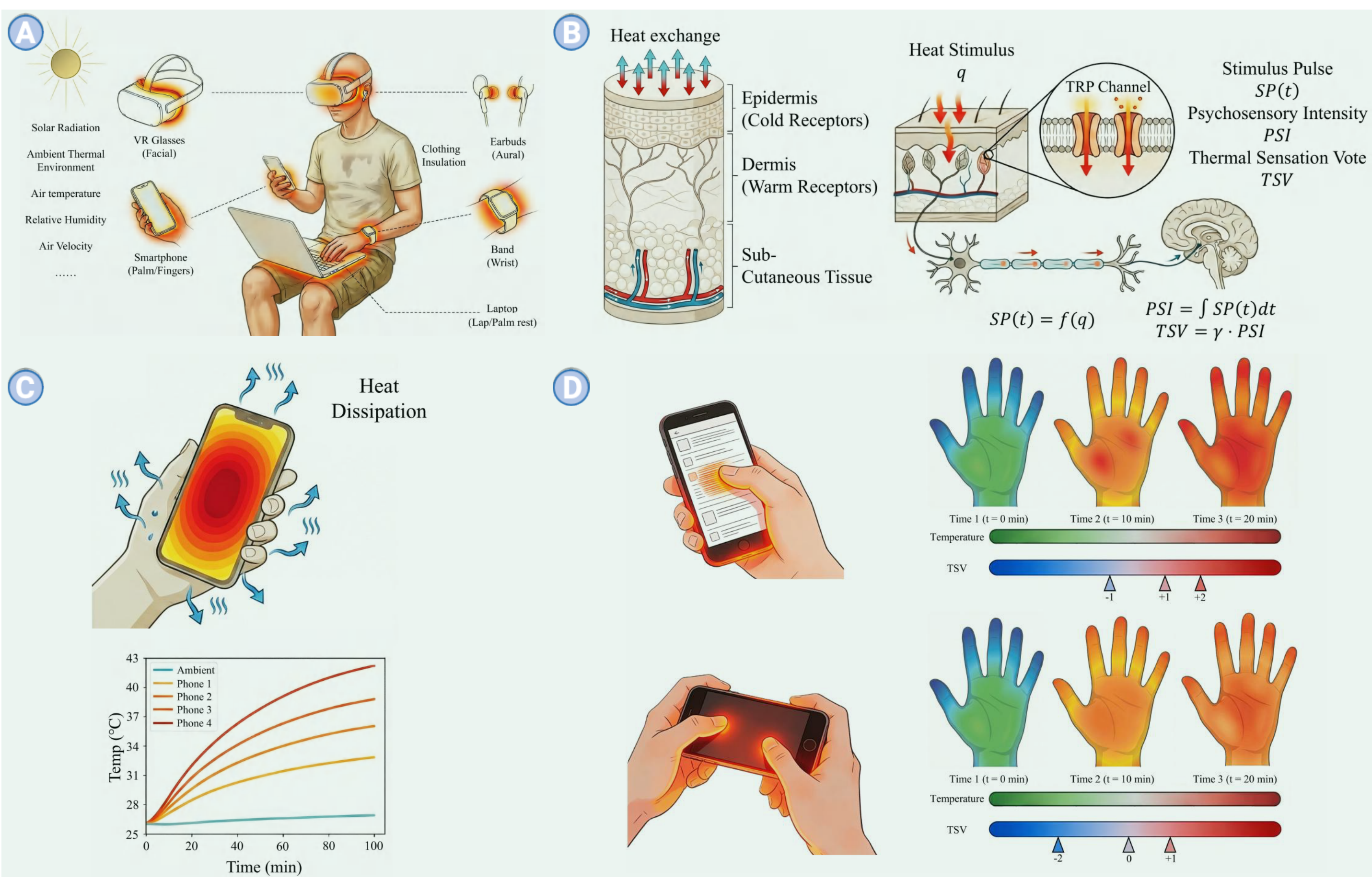

Figure 1. Generation of thermal sensation in consumer mobile devices' contacting scenarios (A) Schematic illustration of thermal contact between the human body and various personal mobile devices, (B) Principles of the generation of thermal sensation, (C) A typical hand-phone thermal contacting scenario, (D) Two usage scenarios exhibiting different trends in the heating up of palms.

with reference to anti-burn safety standards, while comparatively less attention has been paid to the contact thermal comfort from the user' s perspective, particularly without fully considering the effects of differences in material properties and human-device interaction scenarios. For example, at the same temperature of 40 °C, metal, glass, and plastic can produce different thermal sensations upon contact because of their different physical properties. In addition, users may perceive the same degree of device heating differently under different environmental conditions. Evaluating thermal discomfort in such scenarios therefore calls for a re-examination of current assessment methods, particularly of how the dynamic thermal distribution formed at the contact boundary between mobile devices and the human body influences users' thermal sensation and discomfort. To this end, this Commentary proposes a three-level physical-physiological-psychological framework for thermal comfort evaluation. By introducing a refined local heat-transfer model and integrating terminal thermal stimuli with whole-body thermal load, this framework may provide a basis for an evaluation method better suited for contact thermal comfort in mobile devices.

MECHANISMS OF CONTACT THERMAL SENSATION AND COMFORT

Existing human thermal comfort models, whether the classical PMV-PPD model or dynamic thermal comfort models, largely follow an approach that relates whole-body or local thermal load to sensations of warmth and coolness.[1] In essence, they take thermal neutrality, defined by the balance of the human thermal state, as the reference condition and assume that thermal discomfort intensifies as the body departs further from neutrality. Such approaches are effective in built environments characterized by heat exchange over relatively large scales, but their applicability to small-scale localized thermal contact scenarios remains to be further refined. Contact heat transfer is typically characterized by high intensity and pronounced spatiotemporal non-uniformity. Under such conditions, a local body region may experience, within a very short period, a substantial heat-flux impact caused by a large temperature difference, thereby generating a localized thermal load, while the rest of the body may still remain thermally neutral. If thermal comfort is evaluated solely on the basis of whole-body thermal balance, the contribution of local thermal sensation may not be fully captured. Therefore, introducing a modeling approach that uses skin heat transfer and cold/warm receptor signals to characterize psychosensory intensity (PSI) may provide a useful complement to the study of contact thermal sensation.[2]

Taking smartphone-hand interaction as an example, the hand is not only a region with a relatively large specific surface area, but also one in which thermoregulatory mechanisms and receptor distributions are comparatively complex and dense, making it an important and sensitive site for heat exchange between the human body and the external environment. When the hand comes into contact with a heat-emitting device, changes in blood perfusion may accelerate heat dissipation, while sweat secretion may alter the thermal contact resistance The resulting thermal stimulus imposed by the device is therefore jointly shaped by interfacial thermal resistance and internal thermoregulatory processes. In addition, regional differences in thermal sensitivity across the hand mean that the same thermal stimulus may produce different thermal sensations.[3] External thermal stimuli and local thermoregulatory processes together determine the spatiotemporal temperature field at receptor sites. How accurately the epidermal temperature state at this physical-physiological interface is described directly affects the reliability of subsequent predictions at the physiological-psychological level. Therefore, when considering contact-related thermal discomfort, it is necessary to account in a coupled manner for both the externally imposed, non-uniform physical thermal boundary and the body' s internal physiological regulatory processes, and to support the evaluation of contact thermal comfort by constructing a local heat-transfer model capable of accommodating complex, non-uniform spatiotemporal boundary conditions.

MEASUREMENT FOR THERMAL CONTACT BOUNDARIES

In incorporating physiological factors into evaluation methods, a common challenge is that, in current human-device interaction scenarios, the most readily measurable physical quantity is typically the device surface temperature. From a temporal perspective, measurements of steady-state device surface temperature usually presuppose that thermal equilibrium has been reached, whereas actual human-device interaction is characterized by pronounced dynamics. During ongoing heat transfer, the sustained response of thermoreceptors to the rate of temperature change constitutes an important component of thermal sensation. From a spatial perspective, thermal stimuli are non-uniform across the contact interface. Under gripping conditions, the skin surface includes both contact regions and exposed regions, and a conventional lumped single-point temperature cannot accurately characterize such complex spatiotemporal boundaries. Finally, the physical properties of the interface play a critical role in the heat-transfer process. Contact pressure, surface wettability, and the thermophysical properties of materials jointly determine the thermal contact resistance.[4] This means that even when the device surface temperature is identical, the heat flux delivered to the skin may still differ substantially under different contact conditions, thereby leading to different thermal sensations.

Currently used measurement techniques have limitations in characterizing such boundaries. As a non-intrusive approach, infrared imaging can capture transient spatial distributions, but it measures radiative rather than conductive temperature, making it difficult to directly reflect changes in the thermophysical properties of the contact surface, and it cannot perform measurements at the instant of contact when the interface is occluded. Intrusive sensors, by contrast, offer high sampling frequencies and can capture subtle temperature fluctuations, but their measurements are often weighted temperatures across the contact interface. Therefore, before conducting human-subject experiments, alternative approaches that can reproduce physical boundary characteristics in a controlled and repeatable manner are desirable. Drawing on the concept of thermal manikins in built-environment research, biomimetic phantoms for contact thermal testing offer a feasible solution. Phantom materials can be designed to mimic the thermophysical properties of human skin, allow precise placement of sensor arrays, and reproduce boundary conditions such as contact pressure and wettability under controlled environmental conditions. This enables a more quantitative characterization of thermal contact resistance and its dynamic evolution, providing more accurate boundary inputs for linking external physical parameters with internal physiological responses.

TERMINAL-LOCAL-OVERALL THERMAL SENSATION AND COMFORT

In scenarios of thermal contact with mobile devices, heat input at the interface primarily affects local skin regions, inducing changes in local thermal state and local thermal sensation. Although such stimuli typically cause only limited disturbance to whole-body thermal load, they may still influence whole-body thermal perception due to the pronounced local sensations. Existing multi-segment thermal comfort models generally obtain overall thermal sensation through a weighted integration of local segment sensations rather than directly from overall thermal load. Accordingly, in such scenarios, greater attention should be paid to the hierarchical transmission from local thermal load to local thermal sensation and then to overall thermal sensation, rather than relying solely on overall thermal load as the determinant.

Introducing psychosensory intensity (PSI) as an indicator of terminal signals may help capture the influence of high-intensity local stimuli on subjective perception.Thermal sensation arises from the dynamic interaction between local signals and the overall thermal state. Previous studies have often adopted static-weight, gated weighting methods to integrate local thermal sensation.[5] However, in highly non-uniform human-device interaction scenarios with complex boundaries, the use of fixed weights becomes challenging. Thermal sensitivity varies substantially across different regions of the hand, and the number of parameters in static weighting models can easily become unmanageable as regional partitioning is refined. This suggests that a dynamically shifting dominance may exist between terminal impulse signals and overall thermal load. Neural impulses reflect the instantaneous intensity and dynamic characteristics of thermal stimulation, whereas overall thermal load, as a lumped signal, reflects steady-state characteristics. At the level of psychological perception, an interactive inhibitory mechanism may exist between the two. More specifically, when the local PSI signal exceeds a threshold, a local dominance effect may emerge suppressing the influence of overall thermal load so that overall thermal sensation becomes dominated by the local hotspot; otherwise, sensation returns to a baseline state determined by overall body thermal load. According to Stevens and Marks's work, introducing a threshold-based dynamic dominance mechanism may therefore help explain the phenomenon whereby local stimuli determine overall thermal sensation.

EVALUATING CONTACT THERMAL COMFORT OR DISCOMRT

The preceding discussion of the three levels—physical, physiological, and psychological—provides a theoretical basis for constructing an evaluation method. It should be emphasized that the purpose of this Commentary is to propose a conceptual framework and to explore a feasible pathway from measurable physical quantities to the prediction of users' thermal comfort, rather than to establish a fully parameter-calibrated model. The evaluation approach begins with the device surface thermal state. At the physical level, steady-state or dynamic surface temperatures are translated, in combination with a thermal contact resistance model, into heat-flux boundary conditions acting on the skin, providing a basis for subsequent analysis. At the physiological level, these boundary conditions serve as inputs to a hand heat-transfer model, which accounts for local thermoregulatory processes and yields transient temperature states and indices reflecting overall hand thermal state. At the psychological level, physiological responses are mapped to overall thermal sensation through the dynamic integration mechanism discussed above, capturing how local stimuli may influence overall perception.

To support practical application of this framework, experiments can be conducted at each level. Biomimetic phantoms can be used to characterize thermal contact boundaries under controlled conditions, varying contact pressure, material properties, and surface wettability to establish empirical relationships for thermal contact resistance. At the physiological level, hand heat-transfer models can be informed by anatomical data and refined through comparison with infrared thermometry or other measurements. At the psychological level, controlled human-subject experiments can provide preliminary calibration by assessing local and overall thermal sensations under varying stimulus intensity and environmental conditions. Through such an approach, it may be possible to identify patterns such as local dominance effects and to understand their impact on overall thermal perception. Ultimately, this three-level framework may offer a foundation for predicting user thermal perception and guiding thermal design in mobile devices.

CONCLUSION

This Commentary has examined approaches to evaluating contact thermal comfort and thermal discomfort in consumer mobile devices and has outlined a three-level physical-physiological-psychological framework that links measurable physical parameters to subjective thermal perception. At the physical level, the framework considers the dynamic spatiotemporal temperature field at the device-hand interface and factors shaping it. At the physiological level, it accounts for human thermoregulatory responses based on hand bioheat transfer. At the psychological level, it explores how local thermal sensations may be integrated into overall thermal perception through a potential dynamic dominance mechanism.

By integrating these three levels, the framework provides a conceptual basis for exploring how local thermal stimuli influence overall thermal sensation and for informing thermal design considerations in mobile devices. Through further refinement of models and parameters at each level, this approach may evolve into a practical tool for assessing user thermal perception, offering a potential complement to existing design strategies and contributing to improved thermal experiences for mobile device users.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.