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Thermo-Haptics in Virtual Reality

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Abstract: *In the era of ubiquitous computing with flourished visual display in our surroundings, the application of haptic feedback technology remains in its infancy. Bridging the gap between haptics technology and real world to enable ambient haptic feedback on various physical surfaces is a grand challenge in the field of human-computer interaction. To create immerse experiences in the virtual world, we need to explore different human senses (sight hearing, smell, taste and touch). Haptic feedback has an important role in virtual reality and enhancing immersion of user experience. Many different devices have been developed by both industry and academia towards this aim. Although tactile senses are important in daily life because actual contact is how a variety of tactile information is received, current virtual reality technology mostly uses visual and audio senses to physically reproduce the virtual environment. Thermal displays are designed to display thermal indications to make object detection easier in virtual environments. A foundation for analyzing the design of thermal displays is supplied by thermal perception and the mechanism that underlies the processing of thermal information. A vast amount of research on thermo-haptic devices and functional materials has come together to create the basic framework for the creation of wearable thermal virtual reality systems. An overview of thermal perception, different physical mechanisms, and research that may be used in thermal virtual reality technology in the future is given. The review's conclusion examines the advantages and limitations of utilizing thermal display in virtual reality.*

Key Words: *Haptics, Human computer interaction, Thermal feedback, Virtual reality*

I.INTRODUCTION

Temperature has a significant impact on how objects are seen and explored tactilely. Human beings are homoeothermic. This allows him to make thermal exchange by conduction, convection and evaporation[1]. Virtual reality experiences could benefit greatly from the use of thermal displays. Virtual Reality "with the help of engineering makes more senses of the organism become co-opted at least partly and their ordinary inputs are replaced or enhanced by artificial organism is having an experience that was designed by creator", this could be you someone else or another life from such as fruit, fly, tiger etc. While the organism seems unaware of the interface, thereby being fooled into feeling present in a virtual world This unawareness leads to a sense of presence in a virtual world it accepts being naturally[2].

Touch is one of the most important senses in the human body. Touch serves as the primary means by which people interact with their environment. Haptics is described as the means by which information is conveyed through touch[3][4]. Haptics from Greek word 'hapteshai' meaning to touch. In 20th century psychophysicists-initiated haptics field. In the 1970 and 1980s significant research efforts began in manipulation and perception by touch. Initially concerned with building autonomous robots, researcher found the building a skilful hand more complex. Robotics hand should have same abilities as human hand. Find common interest in topic as sensory design and processing, grasping control and manipulation, object demonstration and haptics encoding and grammars for describing physical task in the early 1990 a new usage of the haptics began to emerge[5]. Combination of several emerging technologies made virtualized haptics or computer haptics possible. To increase the user's level of immersion, designers are trying to integrate haptic and thermal feedback methods in addition to the visual stimulation offered by virtual reality[6].

The most recent advancements in thermo-haptics virtual reality technology are highlighted in this study. To identify and discriminate objects in both actual and simulated environments, we first present a historical viewpoint, thermal perception, and the method for processing thermal information. We investigate the functional materials that have demonstrated notable utility in upcoming thermal display devices. We also examine a distinct physical mechanism that regulates the temperature of human skin and related materials that have been suggested as viable options for wearable thermal haptic devices. The literature also discusses heat transfer techniques and the benefits and drawbacks of thermal display systems created by various researchers. A summary of the obstacles and prospects of virtual reality technology follows a description of the current state of thermal haptics devices.

A. Thermoreceptors: The discovery of thermoreceptors has significantly advanced the understanding of temperature perception, revealing distinct pathways for cold and warm sensations. Thermoreceptors, including free nerve endings and specialized corpuscles, play crucial roles in detecting temperature changes and transmitting this information to the brain. The conduction velocities of afferent fibers indicate that cold sensations are perceived faster than warm sensations, with cold receptors transmitting signals at 10-20 m/s compared to 1-2 m/s for warm receptors[7], Type of senses and their respective receptor are mentioned in table no 1.

Types of Thermoreceptors

- Free Nerve Endings*:* Detect extreme temperatures and pain; lack specialized structures.
- Ruffini's Endings: Respond to skin stretching; slow response.
- Pacinian Corpuscles*:* Sense rapid pressure changes; respond to vibrations up to 350 Hz.
- Merkel's Disks: Detect static pressure; slow response.
- Meissner's Corpuscles: Sense light touch and vibrations up to 50 Hz; faster than Merkel's disks.
- Hair Follicle Receptors*:* Contribute to light touch sensation[8]

The understanding of temperature perception, revealing the complex mechanisms underlying how organisms' sense thermal changes. Thermoreceptors, categorized into warm and cold receptors, exhibit distinct physiological responses to temperature variations. This response is mediated through specific ion channels, such as TRPV1 and TRPM8, which play crucial roles in detecting harmful and innocuous temperatures, respectively. Warm receptor, activated at temperatures above 30°C, primarily through TRPV1 and TRPM3 channels, TRPV1 and TRPM3 channels. which respond to noxious heat[9].Cold receptors, Primarily utilize TRPM8 channels, activated by temperatures below 25°C, and exhibit paradoxical firing at extreme temperatures[10]. Thermal information is transmitted via the spinothalamic pathway to the somatosensory cortex (S1). Cold receptors have a higher conduction velocity (10-20 m/s) compared to warm receptors (1-2 m/s), leading to faster perception of cold stimuli[10] Both receptor types exhibit spontaneous firing at normal skin temperatures, with significant changes in firing rates upon temperature fluctuations[10]. The dynamic response of these receptors allows for rapid adaptation to environmental changes, crucial for survival. The integration of thermal information with other sensory modalities remains an area of ongoing research, highlighting the complexity of sensory processing in the nervous system. The flow thermal information process in virtual environment presented in Figure No.1.

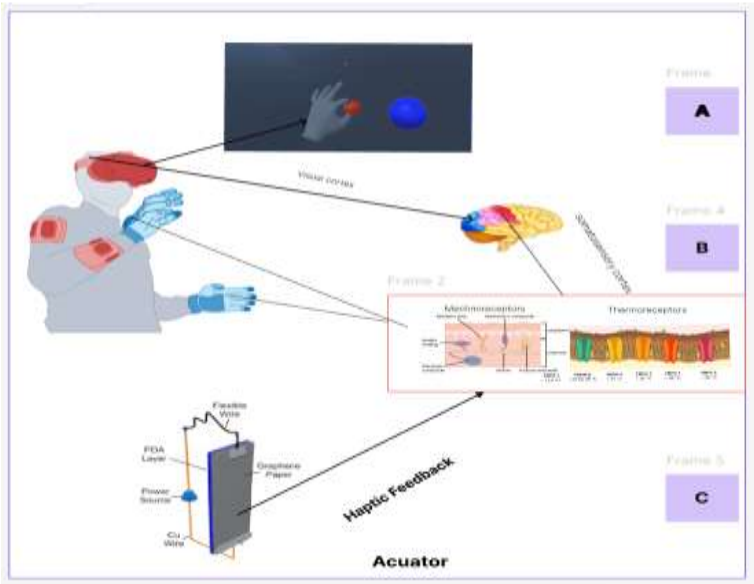

Figure No.1 *(A)VR Interaction, A human grabbing hot object .*

(B) Perception mechanism, Visual and mechanical/thermal tactile sensation reaches the visual and somatosensory cortex, respectively.
(C) Operation mechanism of thermo-touch haptic Neural Pathways Thermal information travels from thermo receptors through the spinal cord to the cortex, with distinct pathways for cold and warm sensations [7].The primary somatosensory cortex and posterior insular cortex are involved in processing thermal information, with a robust representation of cool sensations. The subjective experience of temperature can vary among individuals, influenced by factors such as adaptation and environmental context.

Table No.1 *a classification of the human body senses*

Sense	Receptor	Sense Organ
Vision	Photoreceptors	Eye
Auditory	Mechanoreceptors	Ears
Touch	Mechanoreceptors, Thermoreceptors	Skin, Muscles Skin
Balance	Mechanoreceptors	Vestibular organs
Taste/smell	Chemoreceptors	Mouth, Nose

B. Architecture for haptic feedback

All five senses are used to engage with the simulation, albeit most virtual reality applications nowadays only use a smaller subset, usually touch, hearing, and vision. Users can interact with actual or functional surroundings in virtual reality and see the results of their actions in real time.

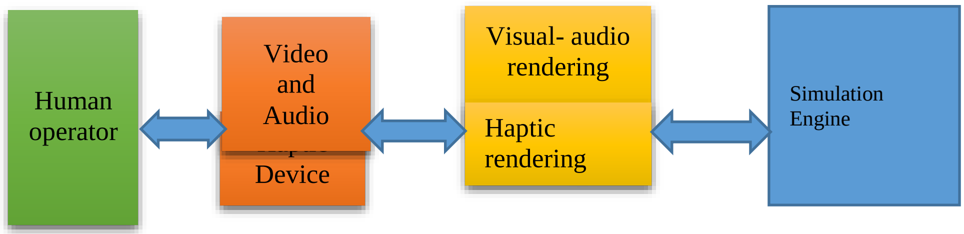

Figure No.2 Architecture for a virtual application incorporation visual auditory, and haptic feedback

Virtual reality applications that provide haptic, visual, and audio feedback. The primary components of the application are-: Calculating the virtual environment over time is the responsibility of the simulation engine. Algorithms for visual, aural, and haptic rendering compute the virtual environment's sound, graphics, and force reaction to the user. Transducers*:* These devices transform computer-generated force, audio, and visual signals into a format that the operator can understand. The haptic interface device is usually held or worn by the human operator, who receives audio-visual feedback from the display. On the other hand, the information and energy movement in audio and channels is unidirectional. The user and the haptic modality exchange energy and information in both directions. Many people consider this directionality to be the most significant aspect of the haptics interaction modality[5].

II BACKGROUND OF THERMAL PERCEPTION

The history of Virtual Reality can be traced back to the 1950 's and 1960s when inventor and researcher explored to "AI". Thermal feedback in virtual reality is part of the boarder field of haptics feedback which refers to tactile sensation that simulates the sense of touch, temperature or pressure. In the beginning of nineteenth century, skin was rarely thought of as an organ with several sensory modalities. The five generally recognized senses were vision, smell hearing, taste and touch[11]. In Erasmus Darwin postulated the presence of more senses in his book. "Zoonomia", in addition to these five senses. Sensation of temperature called a "heat sense[12].

Weber's book, "Touch and Common Sensibility," is titled Der Tastsinn und das Gemeingefuhl. Weber initially distinguished between various attributes of touch. He distinguished between the skin's ability to localise sensation on the body and its ability to sense changes in temperature and pressure. Weber used the Thaler illusion, which makes a cold silver coin on the forehead appear heavier than a similar coin at room temperature, to support his claims that these attributes are interdependent. The various qualities of touch were distinguished. He described how the skin may localise sensation on the body and sense changes in temperature and pressure. Weber used the Thaler illusion, in which a cold silver coin on a surface, to demonstrate his claim that these attributes are interconnected. In order to demonstrate the interdependence of these attributes, Weber used the Thaler illusion, which makes a cold silver coin on the forehead appear heavier than an identical coin at room temperature[11],[13] The evolution of virtual reality technology has significantly progressed since the 1990s, particularly in the integration of thermal feedback to enhance user immersion. Early virtual reality systems primarily focused on visual and auditory experiences, with minimal attention to bodily sensations. However, advancements in haptics technology have led to the incorporation of thermal feedback, allowing users to experience temperature variations that replicate real-world sensations.

In the 1990s, virtual reality systems like the "Virtual Reality Group" arcade machine emphasized visual and auditory immersion, neglecting bodily feedback, including thermal sensations. The 2000s saw the introduction of thermal feedback in haptics systems, with prototypes experimenting to simulate heat and cold, such as feeling warmth from a fire or coolness from snow[14].

Recent developments in thermal haptics, The 2010s marked a shift towards more realistic virtual reality experiences, with companies like Teslasuit developing full-body suits that provide multimodal feedback, including temperature sensations[14],[15].Innovations such as non-contact thermal haptics using ultrasonic phased arrays have emerged, allowing for dynamic temperature adjustments in virtual reality environments, enhancing immersion without bulky equipment[15].Implications for future virtual reality experiences, The integration of thermal feedback has been shown to amplify emotional responses and immersion, particularly in scenarios like virtual disaster simulations[14].As VR technology continues to evolve, the potential for more sophisticated multisensory experiences, including thermal sensations, is likely to expand, offering users a deeper connection to virtual environments. Conversely, while the focus on thermal feedback is growing, some researchers argue that the primary challenges remain in achieving seamless integration and affordability of these technologies, which may hinder widespread adoption in consumer virtual reality [14].

III.THERMAL PERCEPTION

Thermal perception, or thermoception is the ability to sense and perceive temperature , encompassing both the sensation of temperature(warm, cold and neutral) and the subjective experience of thermal and subjective experience of thermal comfort or discomfort[16].The identification of objects through thermal cues relies on the interaction between skin temperature and the thermal properties of the objects. Cold and warm thermoreceptors in the skin play in this process, encoding temperature changes that occur upon contact. The Thermal properties of object, such as conductivity and heat capacity alongside the initial temperatures of both the skin and the object, dictate the heat flux during contact this interaction primary activates cold thermoreceptors, which signal decreases in skin temperature, while thermally sensitive mechanoreceptors provide supplementary information but are less effective in encoding thermal sensations. Cold Thermoreceptors are highly sensitive do decrease in skin temperature are primarily responsible for detecting cool stimuli[10] .Warm thermoreceptors less densely innervated than cold receptors, they respond to increase in temperature but are mechanosensitive[17]. Thermally sensitive mechanoreceptors while they respond to temperature changes, their encoding capacity is significantly lower than that of thermoreceptors, making them less reliable for thermal sensation[10]. The brain integrates inputs from both thermoreceptors and mechanoreceptors to form a cohesive thermal perception, although mechanoreceptors contribute minimally[18].

Despite the established roles of thermoreceptors, some studies suggest that mechanoreceptors to form a cohesive thermal mechanoreceptor may still play a role in the overall sensory experience, albeit indirectly by providing context to the thermal information received. This highlights the complexity of sensory processing in object identification.

A. Afferents Units (Cold and Warm) Afferent units detect and relay temperature changes, with dedicated cold and warm receptors signalling to the brain about temperature variation, crucial for thermoregulation and sensation[19]. Thermo receptors play a crucial role in detecting temperature changes, with distinct responses to innocuous and noxious stimuli. While typical thermoreceptors respond to a range of 5°C to 45°C, pain sensations arise when temperatures fall below 15°C or exceed 45°C[20]. Notably, mild thermal stimuli can activate both thermal nociceptors and standard thermoreceptors, leading to complex sensory experiences. Thermoreceptor activation of thermoreceptor, particular transient receptor potential (TRP) channels, are sensitive to temperature changes, with TRPV1, TRPA1, and TRPM3 playing key roles in heat detection[21]. As directional response concern most thermoreceptors exhibit bidirectional responses, enhancing activity at cooler temperatures and suppressing it at warmer ones[10] .Noxious temperature detection , Nociceptors activate at extreme temperatures, triggering pain responses to prevent tissue damage. Pathological sensitivity, conditions like inflammation can alter thermal sensitivity, leading to heightened pain responses to normally innocuous temperatures[22]). Skin temperature variations can affect thermal perception, causing the same thermal input to be perceived differently among individual [23] the thermally neutral zone is typically between 30°C and 36°C, but can vary based on skin area and individual physiology. The subjective experience of temperature can be influenced by psychological factors, such as expectations and prior experiences, which may alter pain perception and thermal sensation.

B. Thermal threshold When an object held in hand identification by arise in temperature or change in temperature. These changes are encoded by thermoreceptors The ability to perceive temperature variations is influenced by several factors, including the rate of temperature change, baseline skin temperature, and the specific body site stimulated[24][25]. Research indicates that the skin, particularly the thenar eminence, can detect minute temperature differences, with thresholds for warming and cooling being notably sensitive. This sensitivity is underpinned by the roles of specific ion channels and the dynamic nature of thermal perception. The skin can resolve differences as small as 0.02°C to 0.07°C for cooling and 0.03°C to 0.09°C for warming pulses[26][27]. The Weber fraction for cooling pulses ranges from 0.5% to 2%, demonstrating high sensitivity. TRPV1 and TRPM2 channels are crucial for warm-temperature detection, with TRPV1 mediating rapid responses and TRPM2 influencing overall sensitivity[28]. Warm-sensitive neurons (WSNs) are essential for non-painful warmth detection, with fewer than 10% of sensory neurons responding to innocuous warm temperatures. Thermal sensitivity varies with time initial responses can be significantly higher than stable states, indicating a complex interaction between skin temperature and sensory perception[29]. The perception of temperature is not uniform across the skin, with thermosensitive spots showing variability in response and location over time[30]. Thermal feedback can modulate threshold and spatial perception. The skin exhibits remarkable sensitivity to temperature changes, the perception can be influenced by adaptation, leading to diminished sensitivity under certain conditions, particularly with slow temperature changes. This highlights the complexity of thermal perception and the need for further research to fully understand these mechanisms.

C. Thermal adaptation involves the physiological adjustments organisms make in response to prolonged thermal stimuli, allowing them to better cope with varying environmental temperatures. This process can be categorized into physical, physiological, and psychological adaptations, each playing a crucial role in how organisms perceive and respond to temperature changes. Physical adaptations refer to the structural changes in organisms that enhance their tolerance. For instance larger body sixes in certain species correlate with reduced non-shivering thermogenesis (NST)capacity impacting their ability to adapt to cold environment[31]. Physiological Adaptation, involve changes in the body's thermoregulatory mechanisms. Research indicates that complete adaption to thermal stimuli occurs within 25 minutes, particularly in the range of 28℃ to 37℃[32] . The biological thermoregulatory system can alter its properties during repeated thermal exposure, enhancing resilience to extreme temperatures[31]. Psychological adaptation, encompass the cognitive and emotional responses to thermal stimuli. Individual may develop a tolerance to temperature discomfort through repeated exposure in, influencing their perception of thermal sensations[33].

Thermal adaptation in virtual reality enhances user immersion by integrating thermal feedback into virtual environments. This adaptation allows users to experience realistic temperature sensations which can significantly influence their perception of space and presence. The integration of thermal radiation in virtual environments allows user to feel the effect to temperature changes based on their movements and interaction with the simulation. A case study demonstrated that users could dynamically alter their experience by changing their position relative to radiant surfaces, enhancing the realism of indoor climate simulations[34]. Ethermal lightweight thermal feedback solution, conveys temperature sensation through users hands while allowing the use of standard virtual controllers, thus enhancing spatial presence and realism[35].A thermal display glove developed for virtual reality interactions provides rapid thermal stimuli, improving the sense of realism and user engagement by simulating temperature changes in real-time[36].Research indicates that's thermal feedback can alter users perception of distance speed in virtual reality, with higher temperatures making virtual objects feel closer and faster[37].Thermal adaptation in virtual reality offer substantial benefits for immersion and realism, it also presents challenges in terms of technology integration and user comfort. Balancing these factors is crucial for the future development of virtual reality systems.

D. Spatial summation in virtual reality refers to the integration of sensory information from multiple sources to enhance perception and spatial awareness[38]. The perception of thermal stimuli is complex, influenced by various factors including skin temperature, spatial resolution, and individual differences research indicates that while thermal sensations are primarily categorized as heating or cooling, the spatial extent and intensity of these stimuli significantly affect perception. Local and mean skin temperatures play crucial roles in thermal sensation, with higher sensitivity noted in areas like the face hands. The relationship between skin temperature and thermal sensation is linear but local heating is less impactful than cooling[39]. Brain processing of thermal stimuli, distinct brain patterns are activated in response to different thermal stimuli, with early activation in area like the anterior cingulate cortex for intense stimuli. EEG studies reveal that very intense thermal stimuli elicit cortical responses indicating a nuanced processing mechanism in the brain[40]. While the aggregation of thermal stimuli across the skin may limit spatial resolution, it allows for the detection of subtle temperature changes, which is vital for physiological thermoregulation. This duality highlights the complexity of thermal perception and its implications for understanding sensory processing.

Spatial summation can enhance the perception of thermal stimuli when users interact with virtual object. An augmented reality thermal display demonstrated that simulation of skin receptors on the palm and back of the hand resulted in heighted thermal perception[41]. Spatial summation affects contrast detection thresholds with larger stimuli yielding better detection performance. This principle can be applied in virtual reality to optimize visual element for improved user experience[42]. The spatial resolution challenges, the skin poor spatial resolution leads to difficulty in distinguishing temperature variation from multiple sources, as intensity is aggregated across larger areas[23]). Changes in the spatial extent of thermal stimuli do not enhance perceptual performance due to widespread summation[43]. Spatial summation significantly enhances user experience in virtual reality, it is essential to consider potential limitations, such as sensory overload or the absence of certain cues, which may hinder effective navigation and interaction in virtual environments.

E. Spatial acuity in virtual reality encompasses the precision with which users can perceive and interact with virtual environments. The evaluation of skin's tactile spatial resolution has revealed significant insights into the mechanism of thermal perception. While tactile acuity is well documented through various methods, such as gap detection and grating orientation tasks the localization of thermal stimuli presents unique challenges research indicates that the integration of tactile and thermal signals can lead to mislocalization, particularly when adjacent skin area is stimulated differently. This response will explore the key finding regarding tactile spatial resolution thermal perception and the interplay between these sensory modalities. Tactile spatial resolution, acuity is assessed using tasks like the grating orientation discrimination, which measures the smallest grating width participants can reliably distinguish[44]. Factor such as hand posture significantly influence tactile sensitivity with worse performance observed when the hand is oriented sideways[44].A novel haptic device featuring a grid of 16latex bubbles provides localized feedback, allowing user to feel precise interactions with virtual objects. This device achieves a spatial acuity comparable to leasing commercial devices, with a centre to centre separation of approximately 3mm. Such feedback is crucial for reducing the disconnect often left in virtual reality, enhancing the overall immersive experience. The development of system like Acuity allows for high-fidelity visual and auditory representations of users in virtual reality, which is essential for creating immersive experiences. This system processes high-resolution point clouds and audio with minimal latency, enhancing the realism of interaction[45].

Thermal perception challenge, studies show that the ability to localize thermal stimuli is less precise than tactile stimuli with performance decreasing when stimuli are closer to the midline of the body[46].The phenomenon of thermal referral illustrates how thermal sensation can be misperceived due to adjacent tactile inputs leading to a uniform temperature perception across multiple fingers[46] Integration to tactile and thermal inputs, The interaction between tactile and thermal systems can create illusions, as demonstrated by experiments where only two fingers were stimulated, yet all three finger felt cold[46]. The thermal tactile perception is influenced by factors such as temperature resolution ability, which varies with proximity to body temperature[47] .In contrast while tactile acuity is generally high, the complexities of thermal perception highlight the limitations of the thermal senses suggesting a need for further research into improving thermal localization techniques. Challenge remains in ensuring that all user can effectively utilized these technologies, particularly those with varying levels of spatial ability. Addressing disparities is crucial for maximizing the potential of virtual reality as a learning interactive tool.

F. Temporal factor The design of thermal displays must consider various temporal factors that influence the perception of thermal stimuli including temperature change rates, stimulus duration and inter-stimulus intervals. These factors significantly affect how individuals perceive warmth and coldness as well as their reaction times to these stimuli. Thermal stimuli are easily perceptible when presented at rates of at least 0.5℃/s with the perceived amplitude remaining consistent regardless of the rate of change [48] .Slow temperature changes can impact thermal thresholds leading to variation in pain perception and sensitivity[49] . Stimuli typically last between presentations. The intensity and area of effect of stimulus can reduce reaction times for warm stimuli [29] for warm stimuli the threshold varies inversely with the duration of infrared irradiation, stabilizing after one second[48].Prolonged exposure to thermal stimuli leads to adaptation where the neuronal response diminishes over time. For instance adaptation to warm stimuli can take around 25 minutes for certain temperature ranges[29].The perception of warmth and cold has distinct temporal characteristics with warm sensation lagging behind physical stimuli and cold sensations exhibiting a more transient response[50]. The spatiotemporal control of the thermal stimuli can induce sensations such as the thermal grill illusion, The timing and distribution of warmth and coolness can manipulate pain perception[51].Research on apparent motion of thermal pulses suggests that overlapping hot and cold stimuli can create a continuous motion sensation, Further enriching the haptic experience in virtual reality[52].

Devices like ThermoGrasp provide localized thermal feedback, enhancing the realism of interaction with virtual objects by accurately simulating temperature changes during grasping tasks. Challenges remain in achieving consistent and precise thermal modulation across various applications. The effect of temporal summation on cold threshold remains largely unexplored, indication a gap in research that needs further investigate.

G. Thermal referral is perceptual phenomenon where thermal sensation from one part of the body is experienced in another, often without direct stimulation. Research indicates that thermal referral can occur through both tactile and purely thermal stimuli suggesting a complex interplay between thermal and tactile modalities in sensory suggesting a complex interplay between thermal and tactile modalities in sensory processing. Mechanisms of thermal referral, thermal-tactile interaction thermal referral demonstrates how the brain integrate thermal and tactile information, leading to perceived uniformity across stimulated areas. This is supported by findings that show thermal referral result from averaging thermal sensation across multiple fingers[46][53].Adaptation and integration to thermal stimuli occurs before the integration of tactile information indication a hierarchical processing system where thermal perception is first established before being combined with tactile cues[53]. Evidence for purely thermal referral catalo's experiments revealed that thermal referral stimuli. This suggests that thermal referral may not solely depend on tactile input but could also arise from low-thermal processing[54]. Research indicate that combining thermal feedback with vibrotactile cues can effectively create localized thermal sensation on the body, particularly the upper back. Utilizing fewer thermal actuators alongside tactile feedback can yield better response times and accuracy in sensation localization compared to thermal-only setups[55].

Thermal referral significantly enhance immersion, it is essential to consider potential limitation, such as the complexity of integrating these systems into existing virtual reality setups and the need for user adaptation to new sensory inputs. While the predominant view emphasizes the necessity of tactile stimuli for thermal referral the evidence from purely thermal conditions challenges this notion indication that thermal referral may be more fundamental sensory phenomenon than previously thought.

H. Thermal localization The capacity for localizing thermal perception has been explored through various psychological experiments, including the study by [56] the finding indicate that thermal stimulus intensity and proximity to the mid-line significantly affect performance in localization tasks . This overview will delve into the mechanisms of thermal perception, the role thermosensitive spots and the implication spots and the implications of these findings. The thermal perception involves the detection of temperature by peripheral nerves which transmit signals to the spinal cord and brain regions responsible for conscious awareness [23] .The insular cortex and primary somatosensory cortex are crucial for processing thermal information, highlighting the complexity of sensory integration. Research indicates that thermal sensitivity varies across the skin, with specific regions known as thermosensitive spots showing higher sensitivity[30]. These spots are not uniformly distributed, they are more concentrated near the wrist and exhibit inconsistent responses over time, challenging the notion of stable sensory pathways.

Thermal localization in virtual reality involves the integration of thermal feedback to enhance spatial perception and immersion. Recent studies indicate that while users can confidently identify thermal stimuli, their accuracy in localizing these stimuli is often poor[57]. Thermal feedback can significantly influence users' perception of distance and speed, with higher temperatures making virtual objects appear closer and faster[37]. Visual cues in virtual reality can mislead users regarding location of thermal stimuli. Thermal sensations can alter spatial perception, affecting how user perceive distance and speed in virtual reality. Higher temperatures can create illusion of proximity and velocity, enhancing the immersive experience. Thermal feedback can enhance immersion, it may also lead to confusion if visual and thermal cues are not well-aligned, potentially detracting from the overall virtual experience.

I. Thermal design: The design of thermal and haptic displays must be grounded in psychophysical principle to optimize user experience. Understanding the interaction between tactile and thermal senses is crucial, particularly in defining parameters such as temperature range resolution and the timing of stimuli presented. This synthesis of research highlights key aspects of effective thermal display design. Temperature range for thermal displays is between 22℃ for effective thermal cues [58].Ideal temperature resolutions for heating and cooling are 0.001℃ and 0.002℃ respectively[58]. The simultaneity window for tactile and thermal stimuli is approximately 639ms indicating that thermal stimuli should precede tactile stimuli by about 242ms for optimal perception [59].Thermal tactile interaction can lead to perceptual illusion such a thermal referral where uniform temperature is perceived across multiple contact points[46]. Electro-tactile display, temperature influences the voltage threshold in electro-tactile displays, with varying effects on discrimination threshold across different temperatures[60] [61] .

IV. THERMAL HARDWARE PROCESSES

Thermoelectric modules: Thermoelectric modules (TECs) utilize semiconductor materials to converts temperature differences into electrical energy or vice versa. Bismuth telluride (Bi_2Te_3) is the most prevalent thermoelectric material, particularly effective in low-temperature applications. The arrangement of P-type and N-type semiconductors in TEC crucial, as they are thermally coupled in parallel and electrically connected in series, optimizing performance. Thermoelectric materials, Bismith Telluride (Bi_2Te_3), dominates the market for thermoelectric applications below 500K due to its favourable properties[62] . Alternative materials, Lead telluride(PbTe),Silicon germanium(SiGe), and bismuth-antimony(Bi-Sb) alloy are also utilized based on specific application needs[63]. Mechanical and thermal properties, Recent studies show that incorporating materials like $CuGaTe_2$ into n- type Bi_2Te_3 can enhance the thermoelectric performance, achieving a peak ZT of 1.25[64]. Micro Peltier Coolers , Innovations in $(Bi, Sb)_2Te_3$ have led to micro coolers with a maximum cooling temperature difference of 8.9K, showing the potential for miniaturizations[65]. Ceramic plates, material such as aluminium oxide(Al_2O_3) are favoured for their mechanical integrity and thermal conductivity, essential for effective heat transport in TEC[66].While Bi_2Te_3 remains the leading thermoelectric material, ongoing research into alternative materials and composite .

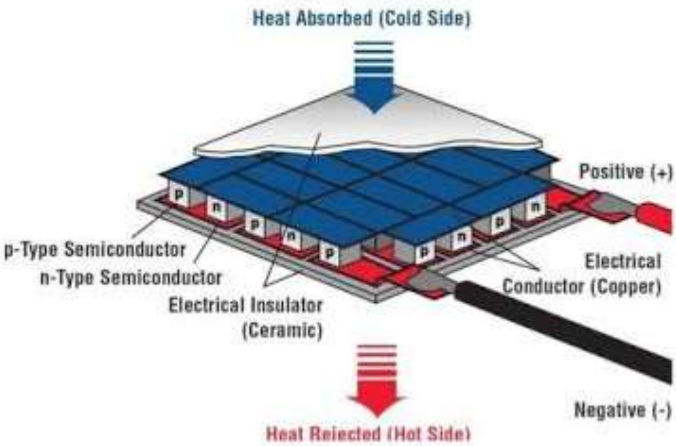

Figure No. 3. *Thermoelectric Module.*

Structures are crucial for expanding the efficiency of and application of range of thermoelectric device, particularly in high-performance scenarios.

A. Electric processes

Joule heating: A fundamental concept of electrical engineering, has found a niche application in Thermal Haptics Displays (THDs) designed for virtual reality and augmented reality. When an electrical current passes through a medium (liquid or solid) with limited conductivity. The amount of heat generated is directly proportional to the square of the current (I), the resistance of the conductor(R) and the time (t) for which the current flows expressed as $H= I^2Rt$. Joule heating, also called resistive or ohmic heating[67]. Joule heating occurs because a conductor collides with the atoms of the material and transfers their energy into heat. A high response rate is essential for THDs to provide realistic thermal feedback. This requires materials with high thermal conductivity and minimal substrate size to facilitate rapid heat transfer. Advances in materials like graphene fibers have demonstrated ultrafast heating and cooling rates, enhancing the responsiveness of THDs[68],[69] . The primary challenges with liquid metals include encapsulation difficulties and potential toxicity. Maintaining their liquid state while preventing leakage is a significant engineering challenge. Additionally, the toxicity of certain liquid metals, such as gallium and mercury, raises environmental and safety concerns. These limitations hinder their widespread adoption in consumer electronics. The future of Joule heating in THDs lies in addressing the current challenges through material innovation and system-level advancements

Achieving a high response rate in wearable heaters is critical for their application in thermotherapy, medical devices and personal heating systems. By optimizing thermal conductivity, reduce substrate size and integrating advanced material, researcher have made significant progress in developing high-performance wearable heaters, to create more versatile and particle heater. Joule heating has emerged as a critical technology in the development of thermal haptics for virtual reality applications. The choice of material plays a pivotal role in determining the performance, stability, and wearability of these devices. While significant progress is essential to overcome existing challenges and realize the full potential of Joule heating in THDs.

Table No.2 *Comparative analysis of material for Joule Heating in THDs*

Material	Key properties and advantages	Challenge and limitations
Silver Nanowires	High electrical and thermal conductivity, transparency, stretchability	Susceptible to oxidation, electro-migration, and network failure
Carbon Nanotubes	High thermal and electrical conductivity, robust mechanical properties, good oxidation resistance	Lower thermal conductivity compared to metals, substrate issues
Conductive Polymers	Mechanically stable	Lower thermal conductivity, potential chemical instability
Liquid Meta	High electrical conductivity, fluid nature for stretchability	Encapsulation challenges potential toxicity

Electrocaloric effect presents a promising alternative to conventional refrigeration method, particularly for wearable cooling devices. This effect relies on the change in entropy and temperature of material when subject to an electric field, allowing for efficient heat absorption or generation. A general equation for electrocaloric effect can be developed based on the pyroelectric effect via the Maxwell relation. The adiabatic change in temperature from an initial value of E1 to final of E2 can be described as follows

$$\Delta T = -\int_{E_1}^{E_2} \frac{T}{C_E} \left(\frac{\partial D}{\partial T}\right)_{S,E} dE \qquad (1)$$

Where D= $\varepsilon_{\circ}E + P$, Where E,P and $\varepsilon_{\circ}$ correspond to the electric field , polarization and vacuum dielectric permittivity $\varepsilon_{\circ} =$ 8.85 $\times 10^{-12}$ Fm^{-1} respectively[70].

The advantages of electrocaloric materials include their compact size. Eco-friendliness and the ability to control temperature changes precisely by varying the electric filed. The effectiveness of electrocaloric materials, such as ferroelectric ceramics and polymers, is influenced by their polarization characteristics and phase structures[71],[72] .The temperature change can be finely tuned by adjusting the electric field, enabling precise thermal management in application like battery cooling[72]. EC systems can achieve higher efficiency compared to traditional vapor-compression systems which have low coefficient of performance[73].The solid-state nature of nature of electrocaloric material allows for easier miniaturization, making them suitable for integration into small devices like wearables[72]. Electrocaloric system do not rely on harmful refrigerants, thus reducing greenhouse gas emissions associated with conventional cooling technologies[73].

Electrocaloric cooling systems can be used to regulate body temperature in wearable devices, enhancing user comfort during physical activity or in hot environments. The compact and flexible design, of EC cooling components makes them suitable for use in portable electronics, where traditional cooling methods may be too bulky or inefficient. The temperature change achieved by current electrocaloric material with higher responses is essential to enhance the cooling performance of EC systems. The periodic application and removal of electric field changes an important area of research. While EC cooling is well suited for small-scale applications, scaling up the technology for larger cooling needs remain a challenge. Investigating the scalability of EC systems and their integration into larger cooling frameworks is crucial for their widespread adoption.

Table No. 3 *Comparison of cooling technology*

Technology	Key Features	Advantages	Limitations
Conventional Vapor Compression	Uses refrigerants undergoing phase changes, high energy consumption, low COP.	Well-established technology with high cooling capacity.	Environmental impact, low efficiency, complex design, difficult to miniaturize
Electrocaloric Cooling	Solid-state operation, high COP, thin, flexible structure.	High energy efficiency, environmentally friendly, suitable for wearable devices.	Limited temperature change requires periodic electric field application.

Magnetocaloric Effect. Magnetocaloric cooling is an innovative refrigeration technology that leverages the magnetocaloric effect (MCE) where material undergoes reversible temperature changes in response to applied magnetic fields. This technology considered a promising alternative to conventional vapor -compression refrigeration systems due its environmental friendliness and high coefficient of performance [74]. The effect allows for heating or cooling by manipulating entropy and temperature through a thermodynamic cycle like electrocaloric (EC) this response provides a detailed analysis of the MC cooling process, material properties and adiabatic temperature.

The MC cooling cycle operates on the principle of entropy and temperature changes in MC material when exposed to varying magnetic fields. During the cooling cycle. Adiabatic temperature increases when a magnetic field is applied to the MC material, its temperature increases adiabatically. This is due to the alignment of magnetic moments in the material, which reduces entropy and releases heat[75]., On heat discharge, the MC material, now at a higher temperature, is connected to a heat sink. Heat is discharged to the surroundings, bringing the material back to its initial temperature[74],[76].Adiabatic cooling after the magnetic field is removed, the material's temperature drops below its initial state due to the randomization of magnetic moments, increasing entropy, This cooling is then used to cool target material [76],[75].

Efficient heat transfer is critical for the performance of the MC cooling system. Several strategies have been explored to enhance heat transfer. Inserting high thermal conductivity material into magnetocaloric materials improves heat transfer within the material and between microcells. This approach has been shown to reduce heat transfer time and increase the maximum temperature span [77]. Coupling Peltier elements between magnetocaloric material transfer, leading to a significant increase in maximum temperature. The reliance on rare earth elements which are often expensive and critical, poses a significant barrier to widespread adoption. Research into cost-effective alternatives such as Ce substitution in GdNi is ongoing[78]. the integration of magnetocaloric materials with heat transfer flids and magnetic field sources requires careful design to optimize performance. Advances in magnetic pumping and system-level simulations are essential for improving reliability and efficiency[77]. While magnetocaloric cooling has shown the laboratory scale, scaling up for commercial application remains a challenge. Continued research into material remains a challenge. Continued research into material synthesis and system optimization is necessary to overcome this hurdle [79]. Magnetocaloric cooling has the potential to revolutionize refrigeration system due to its energy efficiency and environmental benefits. However, its integration into wearable THDs requires addressing challenges related to miniaturization, flexibility and heat dissipation. Advances in thin film magnetocaloric materials and hybrid cooling technologies offer promising solutions. Further research is needed to optimize these technologies for practical application in wearable devices.

Table No. 4: *Comparison of key magneto caloric materials.*

Material	Key Property	Application	Citation
(Mn,Fe)NiSi System	Large isothermal entropy changes at room temperature.	Room Temperature Cooling	[75]
$FeCl_2$	High thermal conductivity and ΔTad near room temperature.	Room Temperature	[80]
$Gd_{1-x}Ce_{1-x}Ni$	Tunable Curie temperature and cost-effective.	Hydrogen Liquefaction and industrial cooling	[78]
Perovskite Manganite's	Wide working temperature range and low hysteresis.	Industrial refrigeration	[81]
$RuCl_2$	High, lattice thermal conductivity.	Room Temperature	[80]

Thermoelectric effect: The thermoelectric effect, commonly referred to as the Peltier effect, is a physical phenomenon that enables the direct conversion of electrical energy into thermal energy making it versatile too for both cooling and heating applications.The Peltier effect, this effect operates by inducing charge carrier in p- or -n type semiconductor to diffuse toward on junction when an electrical voltage is applied resulting in one end heating up and the other cooling junction when electrical field is applied, resulting in one end heating up and other cooling down. Reversing the current direction reverse this phenomenon, allowing for precise temperature control [82][83].

One of the most significant weakness of TE devices is heat management when cooling the skin surface. The TE cooling and heating of the device following equation.

$$Q_c = 2N\left(\alpha I T_c - k\Delta T - \frac{1}{2}R_e I^2\right) \text{ for the cooling mode} \qquad (2)$$

$$Q_h = 2N\left(\alpha I T_h - k\Delta T + \frac{1}{2}R_e I^2\right) \text{ for the heating mode} \qquad (3)$$

Where the first term in parentheses represents the TE cooling/ heating (with α I T_c *and* T_h denoting the Seekback cofficient, electrical current, and temperature of the cold/hot junction respectively) Mean while the second term represents the heat conduction between two TE junctions (with k and denoting the thermal conductance and difference in temperature between the TE Junctions respectively)

The Thrid trem represents Joule heating and its sign convention varis accorfing to the cooling/heating mode[70].

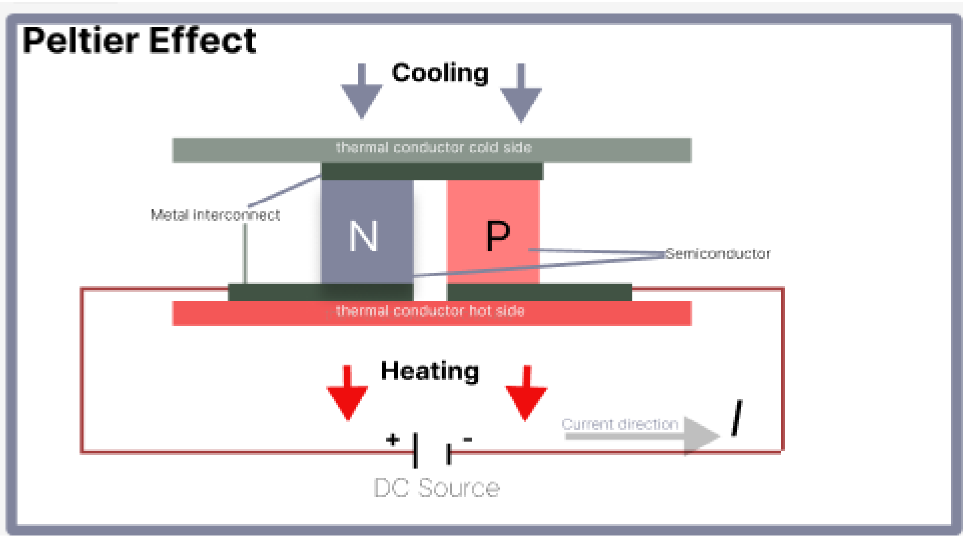

Figure No.4 *A thermoelectric cooler.*

The integration of TE devices into virtual reality systems has opened new avenues for haptic feedback and thermal management Thermoreality, a concept that enhances virtual experiences through thermal feedback, has been explored using TE devices. These devices provide thermal sensations that simulate real-word environments, enhancing the user sense of presence in virtual environments. Wearable TE generators (WTEGS) have also been developed to harvest energy form the temperature difference between the human body and the environment. A cross plane design for WTEGS has achieved high stretchability and output performance, generating a power density of 10.02W/m^2 at vertical temperature gradient of 40 K[83]. Despite the advancement in TE devices for virtual reality application, several challenges remain the thermal conductivity of elastic encapsulation material continue to hinder heat dissipation, leading to performance degradation[84].Additionally the long-term stability and reliability of flexible and stretchable TE devices under repeated mechanical strain require further investigation. Further research should focus on developing high performance TE materials with enhanced flexibility and stretchability. The integration of machine learning techniques for material optimization and device could accelerate the development of the next generation.

Table No. 5 *Key comparison of thermoelectric material*

Device	Temperature Difference(ΔT)	Key Features	Citation
Bi_2Te_3	High ZT at room temperature	Widely used in TE devices for cooling and heating applications	[85],[83]
Mg_3Bi_2	≈91K	Large Temperature difference, suitable for virtual reality applications	[85], [86]
Flexible TE Devices	Substantial skin temperature reduction	Interconnect TE dice with EGaln and Cu electrode, suitable for wearable application	[85],[87]
Stretchable µ-TEG	High sensitivity, rapid response	4x4 vertical temperature sensor array, excellent stretchability and distributed sensing	[88],[89]
Ag_2Te0.6S0.4 Fiber	High tensile strain (21.2%)	Super flexible inorganic TE fiber, high TE performance, suitable for wearables	[88]
Hybrid TE-PCM e-skin	Maintains 35℃ in 10-45℃ range	Combines flexible TE device with phase-change material for thermoregulation	[87]

B. **Non-Electric processes**

Fluidic heat transfer: Fluidic heat exchange systems have emerged as innovative solutions for virtual reality thermal management, particularly in wearable technologies. These systems utilize water or air circulation to regulate skin temperature, enhance comfort and potentially improve cognitive performance, Notably, garment employing elastomeric tubes with aluminum powder and silicone elastomer have demonstrated effective heat conduction, while pneumatic gloves can simulate thermal sensation through temperature-controlled air inflation. However, these systems face challenges in wearability due to bulky components and limited temperature control. Thermoregulatory garments utilize water circulation through elastomeric tubes, achieving a heat transfer coefficient of 98.5m^{-2} K^{-1} ,which is nearly as effective as direct water immersion[90]. Pneumatic gloves, Capable of inducing thermal sensations by inflating airbag with hot or cold air, these gloves achieve a response rate of 2.75℃s^{-1} , demonstrating the potential for rapid thermal feedback[91].

The development of fluidic heat exchange system for virtual reality application present both opportunities and challenges while These systems can provide rapid thermal sensation[73]. There practically is limited by issues such as temperature control and the bulkiness of necessary components. Fluidic heat system can quickly adjust temperatures, enhancing user immersion in virtual reality environments. Wearable potential with advanced, such as the integration stretchable thermoelectric devices, there is potential for creating more compact and efficient wearable systems[92]. Despite limitations, alternative technologies such as skin-integrated haptic interfaces offer promising solutions. The bulkiness of fluidic system, potentially enhancing user experience in virtual reality applications. Advanced cooling textiles show promise in enhancing personal thermal comfort while addressing wearability concerns. Thermal illusions and multisensory feedback have shown promise in enhancing user experience in virtual environments, suggesting that fluidic system may not be the only viable option for thermal sensations.

The elastocaloric effect: The elastocaloric effect in metal alloys, particularly Ni-Ti and Cu-Fe based alloys, is a significant phenomenon where heat is absorbed or released under mechanical stress. The elastocaloric effect involves the adiabatic transformation of austenite to martensite under applied stress, resulting when stress is removed the alloy transition back to austenite , absorb heat and leading to cooling[93]. The efficiency of this process is closely linked to the degree of stress applied, with higher stress resulting in greater temperature changes[94]. The development of elastocaloric and twist caloric materials present innovative solution for solid-state cooling and heating application, particularly in the context of thermal devices. Twist caloric materials, such as supercoiled polyethene rubber, exhibits significant cooling and heating capabilities, with reported temperature changes of 19.1K and 25K,respectively, when subjected to mechanical stress[95]. Ni-Ti alloys are the most studied, exhibiting significant elastocaloric effect due to their shape-memory properties[93] .Cu-Fe-based alloys have also been explored, showing potential for elastocaloric application although less extensively then Ni-Ti[96].Recent advancement in additive manufacturing have improved the microstructure of these alloys , enhancing their performance under strain.

A major challenge is the fatigue stress that affect the durability of elastocaloric materials, limiting their practical applications[97] Research is ongoing to optimize the mechanical properties and thermal efficiency of these materials particularly through innovative manufacturing techiest[98]. The durability and efficiency of the material remain critical areas for further research and development.

Phase change material: Organic phase change materials are increasingly utilized for thermal management due to their ability to absorb and release heat during phase transitions while they offer high thermal energy density and tunable phase change temperatures challenges such as low thermal conductivity, shape retention, and leakage during phase transitions persist, Recent advancements aim to address these issues through innovative composite material and encapsulation techniques. Incorporating graphene oxide into phase change materials such as tetradecanoyl, significantly improves thermal conductivity while maintaining high latent heat, addressing the low conductivity issue of organic phase change materials[99]. The use of expand graphite in high-density polyethylene composites enhances thermal conductivity up to 1.6W/mk, while also stabilizing the phase change material and preventing leakage[100]. The incorporation of melamine foam with paraffin phase change materials prevents leakage and maintain structural integrity during phase changes [101].Techniques like microencapsulation and macro encapsulation are employed to enhances the stability and reliability of organic phase change materials, reducing leakage and improving thermal properties[99].

The integration of phase change materials in thermal management systems, particularly in virtual reality application, presents both opportunities and challenges. While phase change material can effectively regulate body temperature through latent heat absorption and release, their passive nature limits their responsiveness in dynamic environments like virtual reality. Phase changes are widely recognized for their ability to absorb and release heat, making them suitable for passive thermal regulation in building and personal cooling systems[101],[102]. Studies indicate that combining materials with ventilation strategies can significantly enhance cooling energy saving, achieving reductions in energy consumption by up to 96% in certain conditions [101] The primary drawback of phase change material in virtual is their reliance on reaching specific phase change temperatures, which hinders rapid thermal response necessary for realistic thermal sensation. The passive operation of phase change material does not align with the active thermal dynamics required in immersive environments, where immediate temperature adjustments are crucial.

V. THERMAL HAPTICS TECHNOLOGIES

Conduction, convection and radiation are technology of thermal haptics

A. Conduction: In thermal haptics technology for virtual reality, conduction is used to create realistic temperature sensations on the skin of the user**.** Thermal actuators, such as Peltier devices, are used to heat or cool surfaces that meet the user's skin. These actuators can quickly change the temperature of the surface to simulate different thermal sensations. Simulating the sensation of touching a hot metal surface or a cold stone in a virtual environment. The user's skin perceives the temperature change through contact with the thermoelectric cooler[6].Conduction technology in virtual reality encompasses various innovative application. Particularly in remote orchestral conduction and user interaction. A virtual reality system allows conductors to provide visual cues to remote musicians through an avatar, tracing gestures without video streaming, reducing bandwidth requirement , the system maintains tolerable Motion-to-Photon latency[103].Challenges remain in ensuring user comfort and minimizing latency which is critical for effective interaction.

B. Convection: Convection involves the transfer of heat through the movement of fluids (liquids or gases). In the context of thermal haptic technology for virtual reality, convection can be used to create dynamic temperature changes around the user's skin. Fans or air jets are used to blow heated or cooled air onto the user's skin. This creates a sensation of warmth or coolness that changes dynamically with the virtual reality environment. Simulating the feeling of a warm breeze or a cold draft. For example, feeling the heat from a virtual campfire or the chill from an icy wind. Human hands can emit infrared radiation which can be harnessed to manipulate liquid convection patterns without external energy sources. Utilizing human-generated heat for convection control presents cost and sustainable approach , making suitable for applications in bio-chemical sensing with in virtual reality setting[104]. The use U-net convolution al neural network for modelling thermal convection demonstrates the ability to predict fluid behaviours efficiently. This can be integrated into virtual reality to simulate realistic thermal dynamics[105]. The complexity of accurately simulating high Rayleigh number convection and computational demands of real-time processing may limit the extent of these applications in virtual reality environment.

C. Radiation: Radiation is the transfer of heat through electromagnetic waves emitted by material based on their temperature[106]. In thermal haptic technology for virtual reality, infrared radiation can be used to create non-contact thermal sensations. Unlike conduction and convection, radiation can travel through a vacuum, makeit essential in space and high-temperature applications. The user's skin absorbs this radiant heat, creating a sensation of warmth without direct contact. Simulating the warmth from the sun or a fireplace. The user can feel the heat radiating from a source in the virtual reality environment, adding to the realism. Virtual reality training has been shown to significantly reduce radiation exposure among healthcare professionals, with greater decrease in radiation dose compared to traditional training methods [107]. Among patients who experienced anxiety about their treatment,57% indicate that virtual reality session helped alleviate their concerns and patient undergoing radiation therapy improved their understanding of treatment plans , with 74% of participant reporting enhanced comprehension[108]. Virtual reality models that visualize radiation attenuation allow trainees to engage with the concept of radiation exposure without physical risk, promoting a mindful approach to safety[109]. Virtual Reality presents significant advantages in training and education regarding education, it is essential to consider the potential limitation, such as need for technological access and the variability in user experience. The potential benefits of virtual reality in enhancing safety and understanding in radiation -related fields are compelling.

In summary, the integration of conduction, convection, and radiation methods in thermal haptic technology for virtual reality creates a more immersive and realistic user experience. These techniques allow users to feel temperature changes that correspond to the virtual environment, enhancing their overall interaction and engagement.

__Table No. 6__ Thermal haptics work in virtual reality with their contributions and limitations					
Citation	Body Area	Methods	Contributions	Limitations	Application
[1]	Fingertip	Radiator with a thermal resistance of 0.6°C/W, which support a Peltier module. Study how different material affect thermal feedback. This model that describes the thermal exchanges occurring surface texture exploration, based on electrical analogy. Temperature Feedback Range between 5°C to 46°C.	Innovative heat transfer model. Experimental validation. Understanding temperature sensation. Thermal adaptation insights.	Controlled environment. material constraints User variability. Limited temperature range.	VR
[35]	Hands	Combined a controlled experimental design with qualitative interview to comprehensively evaluate the impact of thermal feedback in VR gaming.	Enhanced presence and realism. Integrated with game controllers. Foundation future studies.	Non-counterbalanced order. Limited participant pool. Restricted interaction possibilities. Thermal feedback area.	VR
[36]	Thumb, index finger, middle finger, and palm	Designed using solid works and a 3D mold, The mold was made from an acrylic board and Ecoflex 00-30 silicone, The glove incorporates flexible thermoelectric devices. Use two batteries.	Real-time Thermal Feedback. Gender sensitivity insights.	Sample size. System latency Thermal maintenance challenges.	VR
[110]	Thumb, index and middle fingers, back of hand and forearm.	User test conducted in three distinct stages: only-touch, only thermal and thermos-touch. Focused on structured user testing approach with careful participant selection and equipment.	Introduced a soft wearable, multimodal thermos touches haptic. Diverse feedback type. User -centric Testing. Minimized the thickness of haptic actuator, making it more suitable for wearable applications.	Heat accumulation issues. Lack of new regents. The study acknowledges that investigating appropriate heat dissipation methods remain area for future work.	VR
[111]	Hand	It discusses technique such as polyol, hydrothermal and photochemical reduction methods. Different triggering interaction interfaces.	Comprehensive review of recent advancements in nanomaterial based flexible sensors. It also discusses the role of machine learning in processing sensors data.	Challenge of controlling the size and orientation of material assembly during the fabrication process. Paper does not delve deeply into the specific performance metric of the NMFSs in real-world applications.	VR
[112]	Wearable, Hand and Palm, forearms Feet	Motor-driven Peltier element. Use conduction method.	High-resolution thermal information, Enhanced telepresence experience.	Bulky prototype, temperature control challenges sensitivity of Body Parts Response rate of Peltier elements, Quick feedback is needed.	XR
[113]	Fingers	Use combination of triboelectric and pyroelectric technology integrated with wireless technology.	Enhanced multimodal feedback. Quick response time.	Resolution limitation Complexity of signal processing, Integration of multiple devices is a challenge.	VR/AR

[114]	The design enhances vibration amplitude, effectively stimulated both glabrous and hairy skin	Integration of actuator pair with a thermoelectric cell	Wireless operation, Skin Integrated design Programmable feedback patterns, High efficiency, robust Mechanical design, Custom control schemes.	Spatial Resolution Constraints-The diffusion can affect the precision of localized stimulation make it challenging to achieve distinct sensation in closely spaced area. Size and weight of component. Limited Modes of Mechanical Stimulation. Dependence on temperature control. Potential for user variability.	Sensory augmentation and rehabilitation
[115]	Targeting human body	Constructed using backbone. combined with thermoelectric materials. The STH device employs a feedback control algorithm. Integrated with a finger-motion tracking glove.	Highly soft, stretchable and bi-functional, capable of providing both cold and hot sensations. Rapid response. Accurate thermal sensation.	The use of material like Ecoflex which has relatively high thermal conductivity, can lead to heat loss. Limited thermal range. Potential for overheating.	VR
[116]	Hands	Reinforcement learning Model, Hand tracking technology, Peltier element, Water cooling system.	Just-in-time, Wearable and compact design. Effective cooling system. Customizable sensations.	Power consumption. Dependency on tracking accuracy. Temperature change delay. Complexity of cold feedback.	VR
[117]	Hands and exposed body parts, localized thermal feedback	Prototype development. Simulation techniques (Mathematical and physical laws) Dynamic object behaviour.	Development of the VR Thermal Kit. Realistic thermal simulation. User-centric interaction. Foundation for future research.	Cost and complexity of hardware. Focus on comfort temperature ranges. Need for spatial optimization.	VR
[118]	Face	ThermoVR prototype. Focused on the perception of directional cues. Thermal immersion assessment.	Enhanced user experience. Exploration to thermal variables. Integrated with HMDs.	Physical constraints. Participant comfort. Thermal sensitivity variability.	VR
[119]	Face	Peltier modules were exposed to various thermal stimuli. Key parameters were established for evaluated the thermal patterns.	Dynamic thermal feedback prototype. The accuracy of recognition was found to be approximately 71.84%.	Limited number of Peltier modules. Use comfort issue. Sample Size and variability.	VR
[120]	Face	Qualitative Study Thermal feedback integration. Dynamic thermal patterns. Thermal module design. Recognition accuracy measurement.	Enhance immersion. Focus on thermal sensitivity Quantitative Evaluation.	Limited scope of thermal experiences. User variability.	VR
[121]	Palm	Hapballoon utilized pneumatic actuators to create a lightweight and compact module that can be attached to the fingertips. VR Environment. Integration of components testing.	Innovative feedback mechanism. Lightweight and simple design. Enhanced interaction in VR. Potential for kinaesthetic feedback	Limited feedback area. Challenges in sensory presentation Compatibility issues. General feedback mechanism.	VR
[122]	Forearms Palms, and neck	Wearable thermal feedback system. Physiological signal integration. Physiological feedback loop.	Wearable thermal feedback setup and utilizes water-cooled Peltier elements. Physiological signal integration. Cross-Modal interaction. Machine learning compensation.	Reaction time of TEC elements. Complexity of cross-modal effect. Limited heat capacity.	VR

[123]	Hand	This design includes two independent variables: The type of stimuli and the type of material being tested.	Thermal feedback cluster. Material identification. Real world application.	Intensity rate range-the intensity rating of thermal feedback did not cover the full spectrum (1.0 to 5.0) with the current system only achieving a range from 1.6 to 3.7. Insulation issues, Material discrimination challenges, Lack of threshold measurements.	VR
[124]	Arm and Abdomen	The methodology of this study is comprehensive focusing on the interplay between visual and thermal stimuli in VR, with structured approach to participants engagement and data collectio≈	Provides valuable insights into how visual and thermal stimuli interact in virtual reality, Focused experimentation. Visual stimuli selection.	Limited body parts, Single stimulus focus, Mixed Reception of Visual Stimuli. Need for Broader Visual Stimuli.	VR
[125]	Fingers	ThermoGrasps, a modular device, Targets localized thermal feedback.	Localized Feedback controlled thermal Sensation to the distal phalanges enhancing realism during precision grasps. While interacted with objects of varying temperatures increased immersion and realism.	Challenges remain in achieving seamless integration and user comfort during prolonged use.	VR
[126]	Wrist	Thermal Gill Illusion.	Increased rates of warming with heightened pain perception, Warm-to-cool ratio (higher ratio diminishes the sensation of coldness before pain onset)	Ethical implication and psychological impact of inducing pain in virtual environment, Balancing user engagement with safety and consent remains a critical challenge in virtual reality.	VR

VI. DISCUSSION

Neurophysiological and psychophysical studies offer a framework for improving the design and implementation of thermal displays. It indicates the unique spatial and temporal features of the thermal senses that must be accommodated when presenting thermal feedback. The best method for combining tactile and thermal input in multimodal displays requires further study. how to improve information presentation to improve user performance. The perception of temperature information can be influenced by mechanical signals, and this interaction might be advantageous when conveying information about a distant or virtual object. In conclusion, knowledge on how to show thermal cues in a display to aid in object identification and discrimination has advanced significantly. Numerous research teams have created and manufactured model-based heat displays, which have been verified in physiological and psychophysical tests. A deeper comprehension of the variables influencing the thermal contact. This work will benefit the designing process of thermal displays devices. Main drawbacks of most of the devices are latency, thermal comfort and use methods are not relaxed.

In recent years, a variety of physical mechanisms and traditional techniques for producing warmth and cooling have been used to produce thermal virtual reality systems. The steps to assess whether current physical mechanisms are suitable for usage with thermal virtual reality devices were acknowledged. To overcome their inherent weakness and become state-of-the-art thermal haptic technologies, thermoelectric and electrocaloric devices need to make certain advancements. For thermoelectric and electrocaloric devices, the heat sink structure needs to be reduced in size to increase wearability and preserve cooling capabilities. The business market for virtual reality will keep expanding due to the demand for virtual reality in industrial training, gaming entertainment, and health. Serious injuries could arise from simple errors in extremely dangerous settings. Consequently, virtual reality technologies offer a common and lucrative way to get over these significant drawbacks due to thermal interaction with the surroundings, to increase the level of artificial immersion and produce virtual reality in a more dependable way. The scope of specialized industrial training is expanded by incorporating thermal sensing into virtual reality alongside other existing artificial sensing technologies.

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Conflict of interest

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