A Systematic Review of Thermal and Cognitive Stress Indicators: Implications for Use Scenarios on Sensor-Based Stress Detection

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Abstract. A systematic literature review aiming to identify the characteristics of physiological signals on two types of stress states - single moderate thermal stress state and moderate thermal stress combined with cognitive stress state – was conducted. Results of the review serve as a backdrop to envision different scenarios on the detection of these stress states in everyday situations, such as in schools, workplaces and residential settings, where the use of interactive technologies is commonplace. Stress detection is one of the most studied areas of affective computing. However, current models developed for stress detection only focus on recognizing whether a person is stressed, but not on identifying stress states. It is essential to differentiate them in order to implement strategies to minimize the source of stress by designing different interactive technologies. Wearables are commonly used to acquire physiological signals, such as heart rate and respiratory rate. Analysis results of these signals can support a user to make a decision for taking actions or to make an automatic system undertake certain strategies to counteract the sources of stress. These technologies can be designed for educational, work or medical environments. Our future work is to validate these use scenarios systematically to enhance the design of the technologies.

Keywords: Physiological signal, stress states, thermal environment, stress, affective computing, cognitive load, use scenario

1 INTRODUCTION

Affective computing relates to, arises from, or deliberately influences emotion [1]. Its objective is to allow computers to understand the emotional states expressed by human subjects so that personalized responses can be given accordingly and thus provide an effective and natural interaction between humans and computers [2]. Affective computing systems use physiological features as inputs for emotion detection models [3]. By analyzing, for example, the heart rate variability, respiratory rate, or blood oxygenation, a computer can recognize different emotional states [4]. One of the most studied emotional states is stress. There are several studies on how to perform stress detection by using physiological features [5].

Stress is defined as the application of a certain stimulus ("stressor") that disrupts an individual's normal function [6]. There are different types of stressors (physical, social, psychological, among others) that generate different states of stress. Current stress detection systems focus on either the detection of an overall stress state induced in a laboratory setting by combining multiple stressors to create acute stress [7] or the acute state of stress generated by a high cognitive demand in mild environmental conditions [8]. However, on a day-to-day basis, people are not only subjected to high cognitive demands but also to exposure to moderate high or low thermal environments. These environments contribute to a stress state called thermal stress that occurs when the body perceives high or low temperatures [9]. People spend 90% of their time indoors [10] and, although many of the enclosed spaces have air conditioning or heating systems that aim to improve people's thermal sensation, these are kept at the same temperature, which is often not considered neutral or satisfactory. For example, 43% of workers are not satisfied with the thermal environment of their workplace according to a report conducted by Karmman et al. (2018) [11]. Even more, an individual can be performing a cognitive task at the same time that the thermal environment has an effect on him. Several researchers have studied the relationship between cognitive loads and the thermal environment in schools [12] or workplaces [13] due to the amount of time people spend in these environments. For example, it has been proven that indoor thermal discomfort has an effect on productivity loss [14].

Although we speak of moderate temperatures, they represent a demand for the body and it must use mechanisms to bring itself into balance [15]. According to the literature, the combination of two demands or two single stressors simultaneously has different effects on human responses than when one stressor acts alone [16][17]. This suggests that in order to create a detection system that can detect different states of stress, you need to know the specific responses of these different states; that is, you need to characterize the states produced by each single stressor and the state produced by the combination of two or more of these single stressors. Otherwise, it would be impossible to respond accordingly to the stressor in order to counteract the level of stress produced by the specific source.

Given the fact that the state of stress produced by the combination of thermal and cognitive strains is very common (i.e, in school, university or work environments) and that it would be very important for a detection system to be able to detect this state, this paper aims to review the physiological responses that occur when subjected to single thermal stressors or when subjected to the combination of thermal stressors with cognitive stressors. We will not address physiological responses when subjected to a single cognitive stressor because these responses can be easily found in the literature [8][18]. The features found can be used to design different interactive technologies that work through the acquisition of signals using wearables to identify the state of stress and then perform or implement strategies to minimize the source of stress.

The paper is structured as follows: first, the methodology used to find the physiological indicators in response to the stressors mentioned above is described. Then the results of this review are reported and discussed. From the results, three different use scenarios are presented where physiological indicators could be used to design interactive technologies. Finally, future work and a brief conclusion are presented.

2 METHODOLOGY

The search strategy used for this article is derived from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [19]. Six research databases were consulted in June 2020: IEEE, Google Scholar, PubMed, APA Psycnet, Science Direct, and Web of Science. The search was performed based on titles, abstracts and keywords of English-written publications to exclude duplicated and nonrelevant studies. The complete text of the remaining publications was reviewed based on the following main topics: physiological response, thermal stress, and temperature (T) of enclosed areas. The search terms were then the combination of the following sets of words:

- "thermal stress", "heat stress", "cold stress".
- "environmental temperature", "indoor temperature" and "moderate temperature".
- "physiological signal", "physiological response", "biosignal".

The first set of words aim to find all papers regarding these types of stressor. The second set of words were used to exclude papers that would address excessive thermal stress and would be outside the scope of this review. Finally, the last terms were added to include these stress measurement methods (alone or in combination with others) and to exclude papers that only relied on other forms of stress measurement. For greater accuracy and to find with more certainty studies that included mental processes, this search was made again adding the keywords “cognition” or “cognitive”. These terms encompass any paper that measures cognition or performs some cognitive tasks. Texts published from 2000 onwards were included. The titles submitted were reviewed for relevance and non-repeatability.

The complete selection process can be seen in the following flowchart (Fig. 1). 716 publications were identified and 33 were reviewed. Papers referring to environments other than enclosed ones, as well as those in which some type of physical activity was required (e.g. exercising or driving), were excluded from the review. We did not consider research results where the T analyzed was higher than 40°C or lower than 10°C, nor did we include studies where T varied by steps for acclimatization purposes. Only studies with results related to physiological signals were included and no other method to determine the body’s physiological responses (e.g. cortisol in saliva) was considered.

Signals were categorized into four different systems: cardiovascular, respiratory, nervous, and integumentary systems. For each one of them the increase, decrease, or significant difference of the indicators of each signal was sought. On each reviewed paper different indicators (also their abbreviations, e.g., for heart rate, “HR”) were tracked for each physiological signal of the body systems that changed due to T. Results were divided into “Results of thermal stressors effects on physiological responses” and “Results of combined thermal and cognitive stressors effects on physiological responses”. The subcategories included are the body systems mentioned above.

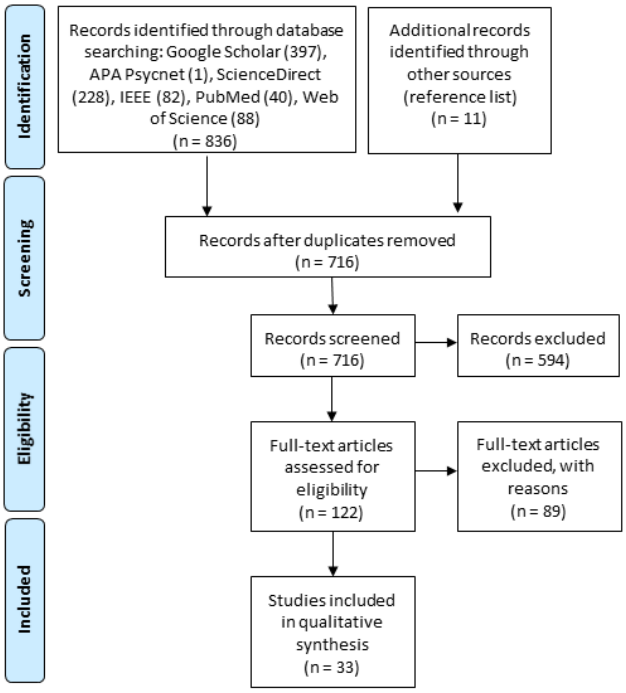

Fig. 1. PRISMA flow diagram [19]

3 RESULTS

To enhance the readability of the following text, Table 1 shows the acronyms of some of the most used physiological indicators, which are grouped according to the human body system to which they belong.

Table 1. Physiological features' acronyms

Cardiovascular system	
HR	Heart rate
RR interval	The interval between two successive heart beats
LF/HF/VLF	High/Low/Very Low frequency activity
BP	Blood pressure
Nervous system	
δ, θ, α, β, γ relative power	Power in δ, θ, α, β, γ frequency bands
Integumentary system	
T	Temperature
Respiratory system	
BR	Breathing rate
SpO2	Oxygen Saturation
ETCO2	End-tidal CO2

3.1 Results of thermal stressors effects on physiological responses

Specific categories of information extracted from the papers reviewed (participants, applied Ts, duration, physiological signals used, and their results) are listed in Table 2.

Cardiovascular system

Some authors agree that heart rate (HR) is higher when T is higher. [21] established that HR increased linearly with T. In [22], the maximum mean HR was seen at 36°C. [23] found HR statistically significantly higher at 30°C than at 20°C. [24] observed that HR increases when thermal conditions depart from the neutral zone (26°C), i.e. when T drops HR rises. On the other hand, in [25], when T dropped from 26°C to 16°C, no significant changes were shown. [26] noticed only a slight difference between cool and warm conditions, a difference that is not significant.

The most studied variable of heart rate variability (HRV) by thermal stress is LF/HF ratio (LF/HF). [27] observed a functional quadratic relationship between LF/HF and room T. Subjects had higher mean LF/HF when exposed both to higher and lower air Ts (from 22°C to 30°C). [28][29] established that ambient T impacts LF and HF. They also found that the minimum value of LF and LF/HF occurred under neutral T (26°C). [30] performed three experiments setting different Ts in a different order to see if the relationship between T and LF/HF variables was affected by the order in which Ts were presented. In two experiments, LF/HF was higher at a T of 21°C and 29°C than at 24°C and 26°C. [31] observed significant differences for each T condition in every frequency variable except for LF. Ambient T has little effect on VLF power according to [29][28]. [31] also performed a temporal analysis of HRV. They found that most of the temporal domain indices values were not significantly different for each T condition. However, the standard deviation of RR intervals (SDNN) commonly showed a significant difference in every T condition.

[25] observed that when T dropped from 26°C to 16°C, average skin blood flow decreased. [32] also found that it increased with T. This was also proved by [24]. [33] found that there are statistically significant decreases in mean BP with a T decrease from 28.8°C to 25.3°C and with a T increase from 18.7°C to 25°C. In another range of Ts, [23] observed that BP was significantly lower at 30°C than at 20°C. [34] performed different experiments with T and found that the condition in which there was the greatest increase in systolic BP was 15°C. At a constant T of 25°C, BP decreased significantly through time in the experiment [35]. Finally, [22] noticed a fluctuating decrease in systolic BP when T rises from 28°C to 38°C.

Table 2. Results of thermal stressors effects on physiological responses

Ref.	Participants	Temperature	Duration	Physiological signal	Physiological response
[34]	2 groups of 8 Subjects All male G1: 20-24 y/o G2: 65-74 y/o	A: AirCon 25°C F: Floor 29°C, air 21°C C: No heating (15°C)	30-min adaptation (25°C) + 90 min on each condition	sT, body T, msT, BP	SBP↑ in C, SBP~ in A and F sT significant change in A and F body T~, msT~ in A and F
[30]	33 Subjects 21 male, 12 female, 23-24 y/o	21, 24, 26,28, 29, 30°C	40 min for each condition	LF, HF	LF/HF↑ 24→21°C LF/HF↑ 28→30°C
[29]	20 Subjects 10 male, 10 female, 21-26 y/o	21, 24, 26, 29°C	Approx. 1 hour per condition	LF, HF, VLF, sT, msT, α, β, ɵ, δ-band	α, β, ɵ, δ band significant change LF/HF↑ when T departs from neutral T VLF~, msT, sT significant change
[28]	20 Subjects 10 male, 10 female, 21-26 y/o	21, 24, 26, 29°C	1 hour per condition	LF, HF, VLFn, α, β, ɵ, δ -Band	21→26°C LF↓ HF↑ LF/HF↓, 26→29°C LF↑ HF~ LF/HF↑ 29→21°C β-band dominant 26°C α-band dominant 24°C α and β-band dominant
[26]	14 Subjects 7 male, 7 female, 19-34 y/o	19, 23, 26°C	30min (23°C) +60min(26°C) +30min (23°C) +60 min (19°C)	HR	HR↑ when T↑
[36]	48 Subjects 24 males, 24 female, 23-27 y/o	26↔38°C G1: Stable G2: 2°C/5 min G3: 2°C/10 min	Depends on the group	sT	when T↓, sT↓ At the same T, sT was higher when T was decreasing compared when it was increasing
[23]	26 Subjects All women >70 y/o	20, 30°C	60 min on each condition	HR, sT, sT, BP	BP↓ HR↑ cT↑ sT↑ at 30°C
[31]	28 Subjects 17 male, 11 female, 19-22 y/o	Approx. 17, 25, 38°C	10 min on each condition	HRV characteristics	LF, HF, VLF significant change at every T, SDNN, RMSSD significant change at 38°C
[35]	200 Subjects 100 male,100 female, 18-29 y/o	25°C	60 min	sT, BP	After 60 min at 25°C BP↓, and sT↓
[25]	30 Subjects All male 18-22 y/o	16, 18, 21, 24°C	30 min (26°C) and 60 min on condition	HR, SkBF, msT	msT↓, SkBF↓, HR~ when T↓
[24]	30 Subjects All male 18-22 y/o	16, 18, 21, 24, 26, 28, 31°C	30 min (26°C) and 60 min on condition	HR, SkBF, msT	sT↑ and SSBF↑ in warm, sT↓ and SSBF↓ in cold, HR↑ when T moves from neutral (26°C) to cold or warm
[37]	50 Subjects All male 20-30 y/o	25, 32°C	30 min (25°C) +35min (32°C) +60min (25°C)	β, ɵ band	ɵ-power↑ and β-power↓ when T changes from 32 to 25°C
[27]	6 Subjects All male 18-21 y/o	22, 24, 26, 28, 30°C	20 min on each condition	LF, HF	LF/HF↑ at 22°C and 30°C
[38]	7 Subjects All male 22-28 y/o	15, 18, 21, 24, 28, 31, 34°C	15 min at 24°C + 65 min on each condition	Attention Level (AL)	First 30 min: AL strongest at 21° C Last 30 min: AL strongest at 24,4°C
[20]	30 Subjects 15 male, 15 female, 19–35y/o	20, 23, 26, 29, 32°C	30 min at 26°C and 60 min on condition	HR, msT, sH	msT↑, sH↑, and HR↑ when T↑
[22]	10 Subjects undergraduate students	28, 32, 36, 38°C	24 h on each condition	HR, body T, sT, BP	max mHR↑ at 16°C SBP↓, body T↑, cT~ from 28 to 38°C
[32] *	16 Subjects 8 male, 8 female, 16-24 y/o	18, 22, 26°C	145 min on each condition	msT, SkBF	msT↑, SkBF↑ when T↑
[33] **	22 Subjects 16 male, 6 female, 20-30 y/o	G1:18.7→25°C G2:28.8→25.3°C	60 min on each condition	BP	mean BP↓ in both conditions
[39]	30 Subjects, 15 male, 15 female, 23-28 y/o	G1:20↔26°C G2:22↔26°C G3:26↔30°C G4:26↔32°C	30 min on the first T + 30-40 min condition	msT	msT↑ when T↑

↔: T changes in both ways, →: T changes in one way, ↑: Increase, ~: No significant difference, ↓: Decrease
sT: skin T; msT: mean skin T; sH: skin humidity; SkBF: blood flow rate
*On this experiment, acoustic environment was also a variable, however it was concluded that PRs were not affected by sound pressure level.
**The CO_2 concentration was different on conditions A and B, therefore these results are also influenced by this factor.

Nervous system.
In two research papers, [28][29] showed significant differences of α, θ, δ β -band among the temperatures studied. They also identified dominant bands in every T. β-band is dominant under ambient T of 21°C and 29°C. α-band under 26°C. At 24°C α-band and β-band were equally regnant. In the experiment of [37], θ-power increased, and β-power decreased when T changed from 32°C to 25°C. [38] found that the power of EEG analyzing attention is stronger at 21°C during the first 30 minutes and at 24°C during the last 30. At the end of the experiment, the highest power was observed at 27.6°C. T of 14.6°C was the worst condition for attention during the whole experiment.

Integumentary system.
[22] showed an increase in skin T when ambient T rises. [23] found that calf T was higher at 30°C than at 20°C. [36] drew other conclusions: local skin T changed less as T decreased than as it increased. Local skin T linearly changed with ambient T in a stable thermal environment but nonlinearly in the unstable thermal environment. [29] analyzed local Ts on different body parts. When environmental T varies from 21°C to 29°C, local Ts that changed in the following descending order: foot, anterior calf, hand, forearm, and anterior thigh T. The body parts with the lowest changes were the forehead, chest, abdomen, and scapula. [34] experimented with three conditions (C: no heating 15°C, F: floor heating at 29°C, air at 21°C and A: Air conditioning at 25°C) to monitor each local body location skin T, except abdomen and ilium, finding that these were significantly affected by the conditions proposed by the authors. Significantly higher Ts were found in the forearm, hands back, palms and thigh front for condition A than for condition F, but the opposite occurred in T of the instep and sole. Most local skin T resulting from condition C were significantly lower than those for conditions A and F. [35] maintained a constant T of 25°C for 60 min; in this time, oral T and skin T decreased.

[34] did not find significant differences in rectal T between conditions A and F. [23] observed that body T was higher at 30°C than at 20°C. Furthermore, in the experiment of [22], rectal T fluctuated from 36.6°C to 37.46°C among different conditions. [21][24][32] stated in their experiments that mean skin T was positively related to T. More specifically, [25] explained that in general when T dropped from 26°C to 16°C, mean skin T dropped from 33.8°C to 30.9°C. [29] established that when ambient T rises, mean skin T will markedly increase while the maximum difference of skin T all over the body will markedly decrease. [39] observed the same pattern: the lower room T, the lower the mean skin T. [32] observed that at high ambient Ts, skin humidity increased rapidly with an increase of T.

3.2 Results of combined thermal and cognitive stressors effects on physiological responses

The papers mentioned in this section conducted experiments where participants had to perform cognitive activities while exposed to a thermal stressor. Specific categories of information extracted from the papers reviewed (participants, applied Ts, duration, physiological signals used, and their results) are listed in Table 3. In this table, the name of the applied cognitive activity and a brief description of it can be found.

Cardiovascular system.
In the experiments of [12] and [40], subjects had to perform a neurobehavioral test at different Ts. During both experiments, an increase in HR was found at the condition with higher T. [41] obtained a similar result where HR was higher at 27°C than at 23°C while subjects performed both office and neurobehavioral tests. In a previous study, [42] observed that HR was lower at 22°C compared to 30°C; it also decreased during each exposure independently of the condition. [43] established that HR increased with increasing T; they used attentional tasks at different Ts. [44] measured HR before and after the cognitive task; they observed that students HR at the end of cognitive activity was the only value with a significant difference between exposures. According to their study, both the final and mean HR of individuals increased throughout exposure to high Ts. On the other hand, [45] conducted a study with a T condition lower than neutral (10°C) while performing a cognitive task and found a slight decrease in HR. [46] used the a continuous performance task test and evidenced a significant difference between HR at air Ts. [15] found a significant relationship between maximum HR and Ts while doing a reasoning test battery. Contrary to that, [47] found that HR values were higher at 22°C compared to 26°C, but in this study, subjects were students exposed to a 2-hour lecture.

[40][41][43] agree that pNN50 (proportion of successive heartbeat intervals that differed by more than 50 milliseconds) decreased significantly with increasing T while doing the respective cognitive tasks of each experiment. [46] did not find significant differences in HRV temporal-domain parameters in baseline and exposure conditions with different air Ts, but there was a significant difference in mean values of LF/HF. Moreover, a significant difference was found between mean values of RMSSD (Root mean square of successive heartbeat interval differences), LF/HF, and SDNN in task conditions with low workload, medium workload and high workload in comparison to the baseline considering the Ts of the experiment. The physiological signals in the experiment of [48] were measured while the participants were reading a book or playing games. They found that LF/HF increased with air T, but there was no significant effect. In the experiment of [47], LF/HF was higher at 26°C compared to 22°C while indices of HF were lower at 26°C compared to 22°C.

[12] measured physiological signals before and after the neurobehavioral test, finding that amplitude variations in diastolic BP before and after the test were small at 26°C but large at 29°C. [44] also measured BP before and after the reasoning test and determined that BP levels' distribution was similar between the three experimental conditions. In cold (10°C), BP was significantly higher compared to control (25°C) [45]. [49] made different analyses with T changes and cognitive load concerning BP. It increased with work stress regardless of operating T. On the other hand, if operating T was increased from 18.7°C to 25°C, BP was reduced only when in seated state (not while neurobehavioral tests were being performed). Furthermore, by lowering operating T from 28.8°C to 25.3°C, BP was lowered only in a seated state. In [43], no significant differences were found in BP between Ts.

Table 3. Results of combined thermal and cognitive stressors effects on physiological Responses

Ref.	Participants	Temperature	Duration	Physiological signal	Cognitive assessment tool (CT)	Physiological response
[45]	10 Subjects, all men, 20-26 y/o	10, 25°C	90 min (25°C) and 120 min (10°C)	sT, HR, body T, msT, Oxygen consumption, BP	ANAM-ICE: code substitution, logical reasoning, matching to sample, continuous performance, simple reaction time, Stenberg memory search.	sT ↓, HR ↓, Oxygen consumption ↑, BP↑, cT↓, msT↓ at 10°C
[50]	96 Subjects, 48 males, 48 female, 20-23 y/o	20, 23, 26°C	Approx. 250 min on each condition	sT, msT	Measures of mental performance of the subjects were obtained from various tests, i.e. arousal/alertness, concentration, creativity, and reasoning.	sT ↓ when T↓, msT decreases with time
[48]*	21 Subjects, 15 male, 6 female, 18-20 y/o	17, 21, 28°C	120 min on each condition	LF, HF, α, β, δ band	Office work: typing and addition tasks. Neurobehavioral: Mental reorientation, Grammatical Reasoning, Digit span memory, Number calculation, Stroop test.	LF/HF ↑ at 28°C, δ band↓, α and β band~ at 17 and 28°C
[42]	12 Subjects, 6 female, 6 male, 21-25 y/o	22, 30°C	The whole exposure lasted 4.5h	HR, respiratory ventilation rate (RVR), SpO2, ETCO2	Office work: typing and addition tasks. Neurobehavioral: Mental reorientation, Grammatical Reasoning, Digit span memory, Number calculation, Stroop test.	HR↑ RVR↑ ETCO2↑ SPO2↓ at 30°C
[40]	12 Subjects, 6 male, 6 female, 21-28 y/o	27, 35°C	3 hours on each condition	HR, pNN50, BR, RVR, msT, ETCO2, SpO2,	Neurobehavioral: Mental redirection, grammatical reasoning, digit span memory, visual learning memory, number calculation, one-digit multiplication, Stroop test, visual reaction time.	msT↑, HR↑, pNN50↓, SpO2↓, ETCO2↑, BR~ at 35°C, RVR significant different at sometimes of CT.
[44]	28 Subjects, 23 male, 5 female, 17-30 y/o	Approx. 22, 23, 28°C	Not specified	HR, BP	Reasoning test Battery 5 (BPR-5) (abstract, verbal, numerical, spatial, and mechanical reasoning)	HR↑, BP~ at 28°C
[43]	32 Subjects, 16 male, 16 female, College students	26, 30, 33, 37°C	175 min on each condition	HR, BR, BP, sH, SPO2, ETCO2, sT, body T, msT,	Visual reaction time, Stroop test, redirection, overlapping, addition, multiplication, visual learning	sT↑, HR↑, ETCO2↑, SPO2~, SBP~, BR~, pNN50↓, body T↑, msT↑, sH↑ at 37°C
[49]	22 Subjects, 16 male, 6 females, 26-28 y/o	G1:20→25°C G2: 28→25°C	90 min on each condition	BP	Office work: Visual reaction time, subitizing, Stroop test, backward corsi block-tapping, N-back test, typing	BP↓ in both conditions
[46]	35 Subjects, all male, 20-30 y/o	18, 22, 26, 30°C	50 min on each condition	α, β, ɵ, δ band, BR	N-back test (3 levels of different complexity)	HR, BR, RMSSD, LF/HF, SDNN significant changes
[47]	20 Subjects, 14 male, 6 female, 18-24 y/o	22.4, 26.2°C	140 min	HR, LF, HF, BR	2-hour university lecture and the Cambridge Brain Science Cognitive Evaluation Tool	HR↓, LF/HF↑, HF↓, BR~ at 26.2°C
[15]	360 Subjects, 252 male, 108 female, 18-30 y/o	20, 24, 30°C	Approx. 1 hour on each condition	HR, BP	Reasoning test Battery 5 (BPR-5) (abstract, verbal, numerical, spatial, and mechanical reasoning)	max HR and BP significant changes
[51]	15 Subjects, 22-33 y/o	21.7, 25.2, 28.6°C	Approx. 1 hour on each condition	Mental workload (MWI)	Computer-based cognitive task: Number addition, Forward digit span, choice reaction, and visual search.	↑ MWI at 28.6°C
[41]	12 Subjects, 6 male, 6 females,18-30 y/o	23, 27°C	Approx. 2 hours on each condition	HR, pNN50, BR, SPO2, sT, sH	Office work: typing and addition tasks. Neurobehavioral: Mental reorientation, Grammatical Reasoning, Digit span memory, Number calculation, Stroop test.	sT ↑, sH↑, HR↑, pNN50↓, BR↑, SPO2↓ at 27°C
[12]**	12 Subjects, 6 male, 6 female, 12-14 y/o	26, 29°C	Approx. 80 min on each condition	HR, BP, body T	Neurobehavioral: letter search, Stroop test, graph overlapping, stereoscopic vision, Schulte grid, tow-digit search, visual pattern, visual retention, memory scanning, symbol digit, event sequence, serial addition, serial subtraction.	HR↑, BP~, body T↑ at 29°C, after CT, variation of BP before and after CT was greater at 29°C

↔: T changes in both ways, →: T changes in one way, ↑: Increase, ~: No significant difference, ↓: Decrease; sT: skin T; msT: mean skin T; sH: skin humidity; SkBF: blood flow rate; CT: Cognitive Task

* Only 3 subjects had their physiological signs measured.

** In this paper the effect of air velocity was also measured, the conditions of the experiment included not only different temperatures, but also different air velocities (0.1, 0.6, and 1.0 m/s).

Nervous system.

[51] measured mental workload from the frequency bands. In general, the mental workload was the highest at 28.6°C among the thermal conditions. Another conclusion of this study was that with a similar mental load, a lower performance was achieved at 28°C, which means that subjects must make a greater effort to maintain their task performance in a warm environment. On the other hand, they also observed that changes in ambient T causes the mental workload of some subjects to increase but for some others to decrease. More specifically, [48] analyzed power frequencies of ECG while the participants were reading or playing games. They found that the power of δ-band EEG was significantly affected by air T; it decreased at 17°C or 28°C compared with neutral condition (21°C). Also, α-band and β-band EEG increased at 17°C and 28°C, but the change was not significant.

Integumentary system.

[41] found that T at temple and hand were systematically higher at 27°C than at 23°C while doing office tasks and neurobehavioral tests. Temple T increased significantly when increasing air T in the experiment of [43]. [50] noticed that changes in skin T depended on where it was measured. Forehead T experienced the least fluctuation under all conditions and was the warmest of all measured locations. Something similar happened with T measured on the back and torso. However, T of extremities was different. T of hands and feet at 26.0°C was maintained, while at 20.0°C and 23.0°C it decreased with time of exposure. With a lower T (10°C), [45] found that T of fingers decreased by 15.3°C–16.1°C compared with control conditions (25°C).

In cold condition (10°C), rectal T decreased by 0.3°C-0.4°C in the experiment of [45]. Similarly, [43] observed an increase in eardrum T as air T increased. [12] also found that body T was higher at 29°C than at 26°C. Moreover, at 29°C, the difference between body Ts before and after the test was larger than that at 26°C. The behavior of mean skin T was consistent with the results mentioned above. It was significantly higher as air T increased in the experiment of [43]. Similarly, in [40] experiment, mean skin T was higher at 35°C than at 26°C. In cold T (10°C) in [45], mean skin T dropped by 6°C-6.4°C compared to control (25°C). [50] noticed that mean skin T decreased with time in all conditions. [43] reported a significant increase in temple moisture at a T of 33°C compared to 26°C and 30°C. Besides, [41] observed that absolute humidity of skin in the temple was the same in the conditions at the beginning of exposure, and then gradually increased, more at 27°C than at 23°C.

Respiratory system.

In the experiment of [41] BR was measured at the end of a cognitive task; it was higher at 27°C than 23°C. [46] found that independently of the cognitive task, air T influenced BR, but they also reported a significant difference between mean BR changes in task conditions with the low workload, medium workload and high workload and different air Ts. On the other hand, [47] observed no differences in BR between both T conditions. This was also the case of [43]. [40] found BR to be higher at 35°C compared with 26°C but not significantly. [42] found that respiratory ventilation rate was lower at 22°C than at 30°C. At 22°C, it decreased during exposure, and at 30°C, it decreased at first and then increased.

ETCO2 increased significantly with increasing T except between Ts of 30°C and 33°C in the experiment of [43]. A similar result was observed by [42]. Although they measured the variable at the end of the cognitive task, they found that ETCO2 was significantly higher at 30°C than at 22°C. On the other hand, [40] [40]observed the opposite, although not a significant difference was found, they noted that ETCO2 was lower at 35°C than at 26°C, and it tended to decrease throughout each exposure under each condition. In [43], SpO2 did not decrease with increased T nor increased. [40] and [42] found at the end of their experiments a significantly lower SpO2 among the higher Ts. [41] observed an increase in SpO2 overtime at 23°C, and it was lower at 27°C. [42] also found that with 22°C air T, SpO2 did not change significantly between the two periods in which measurements were taken; however, it increased significantly after 15 minutes of resting at 30°C. Finally, [45] measured oxygen consumption and found that this increased from 17% to 26% in the cold condition (10°C) compared to the control (25°C).

4 DISCUSSION

4.1 Thermal stressors effects on physiological responses

HR has been used as a proxy of thermal stress [42][43]. There is a consensus that when T rises, HR also increases [20][22][23]. These experiments have a T range of at least 10°C; therefore it is more likely to see changes in this variable. At low Ts, there is no clear pattern in the behavior of HR, in some experiments, it increases as T drops [24], whereas in others there is no significant noted difference [25][26]. LF is related to sympathetic and parasympathetic activity, HF infers vagal activity [52]. LF/HF value indicates which type of activity is dominant. Theoretically, if LF/HF is greater than 1, sympathetic and parasympathetic activity is stronger than vagal, placing people in a state of arousal and stress; if it is less than 1, people are in a state of rest or sleepiness, and if LF/HF equals 1, people are in a state of arousal and comfort [28][53]. Authors agree that LF/HF follows a quadratic function [27][28][29][30]. The lowest value of the function is close to 26°C, a neutral T, and differences between the closer Ts (±2 °C) are not as noticeable. However, those differences become more significant as T increases or decreases, moving further away from neutral T (approx. from 2°C to 8°C further away).

The three studies that evaluated skin blood flow rate agree that it is positively related to ambient T regardless of the direction in which it changes [24][25][32]. Under high-T environments, the body's sympathetic nervous activity slows, as a consequence, skin vasodilates to increase blood flow and skin T, thus heat dissipation is strengthened [22]. However, skin blood flow was not evaluated with warmer Ts, so it would be interesting to investigate the behavior of this variable at Ts higher than neutral. There is not much consistency in BP's behavior, because of different T ranges and variations between experiments. Several authors showed that BP is lower at high Ts and higher at low Ts [22][23][34], but further analysis is required in order to draw concrete conclusions.

According to the results, four bands α, θ, δ, and β could be indicators of T changes because they show significant changes with only a 3°C difference. Especially β-band shows dominance in some specific T ranges when they move away from the neutral T [28][29]. β power widely represents human cognitive function and can also be narrowly correlated to attention and perception [54]. Only one paper was reviewed that analyzed attention [38], and its results show that more experiments should be done with different exposure times and at different Ts because attention level changes according to these variables.

Skin is essential for T regulation, it provides a sensory interface between the body and the external environment [55]. There is a wide agreement between authors regarding body T. There is a directly proportional relationship between T of the environment, mean skin T, and local body Ts [22][23]. The T of the extremities has a greater variation than that of other parts of the body when changes in ambient T occur [29][34]. Only one study evaluated skin humidity [20], therefore more studies are needed to draw accurate conclusions, especially in colder environments where this variable was not evaluated.

4.2 Combined thermal and cognitive stressors effects on physiological responses.

HR behaves similarly when cognitive tasks are developed in warmer Ts to when they are not, it tends to increase when T rises [12][40][41][42][43]. This could be since, to ensure oxygen supply to the brain, it is necessary to increase HR [12]. It would be interesting to investigate further the effect of the combination of both stressors, and, in the case of [46][46] and [15], to review if these significant changes are due to T, cognitive load, or both combined. Some temporal HRV parameters require further study in moderate thermal environments with cognitive loads since no significant difference is found when evaluating different Ts. However, when adding cognitive tasks, a difference between them is found [46], indicating a relationship between both stressors in the body. LF/HF continues to be a promising indicator since, in addition to differentiating Ts, it also presents significant changes between levels of difficulty in cognitive tasks. More information is needed on behavior of LF/HF at different Ts, with different cognitive tasks, and at different levels of these cognitive tasks.

The combination of stressors (cognitive and thermal) have different effects on BP depending on the experiment. [49] observed that BP is changed by the cognitive task regardless of T condition, one hypothesis for this could be that one of the two stressors acts on the other and overrides it, but more research is needed to prove this. On the other hand, [12] found that variation of BP between before and after the cognitive task is different for each T, so there may be an effect of both stressors. On the contrary, [44] found no significant differences in this variable. Because of the previous inconsistency, more research is needed to draw stronger conclusions about BP response to changes in T with or without cognitive load.

Regarding the nervous system, only two studies were found that used measurements from an electroencephalogram, but they are not comparable because one used power bands separately [48] and the other measured mental workload [51]. However, the increase of the task demand results in a significant increase in θ-band activity of the frontal lobe and a decrease in the α-band activity of the parietal lobe [56][57]. According to this, it would be worth studying the behavior of these bands exposed to different mental loads with different Ts.

Local Ts have a similar effect when doing cognitive tasks or without them. There is a positive relationship between T of the environment, local Ts [41][43][45], mean skin T [40][43][45][50] and body T [43][45]. There is evidence that a slight increase in body T could reduce lapses in attention, improve self-perceived alertness, and elevate neurobehavioral function [58]. It was also found that there is less change of sT in the central parts of the body than in the extremities [50]. It would be useful to investigate the effects of both stressors separately to see if completion of a task increases or decreases its effect on body T. For skin humidity, only two papers were found that measured its change [41][43], and they found that the higher the T, the higher the skin humidity.

There is agreement among authors that BR rises due to increased T [40][41]. [46] found that BR changes because of T, regardless of the cognitive task, but it also changes because of task difficulty at different Ts. This suggests that BR is a good indicator for identifying the combination of stressors. For ETCO2, there is an agreement among authors that it increases with increasing T while performing some cognitive activity [42][43]. This indicates insufficient alveolar ventilation [43]. To better understand this variable, one should compare studies that evaluate it at the same moments of the cognitive task (during or at the end of it). Also, the effect of T alone should be evaluated to see if cognition has a significant effect on these changes. Results of SpO2 are diverse. Some authors do not find significant changes in it [43], while others find that the higher the T, the lower the SpO2 [40][41][42]. It is reiterated that changes in these indicators must be studied independently to see how much of each stressor contributes to the changes in the variable.

4.3 Limitations

One of the limitations of this review is that PR caused by only cognitive stressors was not evaluated, only thermal stressors independently were reviewed, and the combination of them with cognitive activities. On the other hand, T ranges, samples, and physiological sensors in each study differ, causing variations in the results of the experiments. Finally, cognitive tasks in each experiment evaluate different cognitive functions of the brain and generate a varied strain depending on the difficulty of the task.

5 IMPLICATIONS OF THE REVIEW RESULTS: THREE USE SCENARIOS

Based on the above result analyses, in this section we present three use scenarios in three contexts– work, education and health. Subsequently, we explore the feasibility of their realization as future work.

5.1 Work context

Some studies state that one way to improve productivity at work and reduce absenteeism is through a satisfactory thermal environment [13]. There is evidence that a slight increase in body T could reduce lapses in attention [58], affecting worker productivity. According to the review, physiology changes at higher or lower temperatures than a satisfactory thermal environment (approx. temperature 26°C [26]). With this information, it is possible to design different interactive technology that can detect and act upon stress. According to the results, the physiological features that can identify the state of thermal stress are HR, LF/HF and Body T. Accordingly, different sensors acquire the electrical signals of the heart and the temperature, for example, a smartwatch or any wristband that measures the heart rate and infrared thermometers. These sensors can be implemented in offices, i.e., small infrared thermometers can be placed on computer screens and measure the temperature of workers from time to time. Also, these sensors can be interconnected, and data can be sent to a cloud-based server serving as an IoT platform to provide group or personal reports and respond to thermal changes within the office. The features can be processed to identify the states and levels of stress using machine learning algorithms such as neural networks and support vector machine, which are widely used in the literature to detect stress and other emotional states [59].

Thus, it is possible to design an air conditioning or heating system that lowers or raises the temperature of the offices according to the physiological signals of the workers and that makes temperature adjustments until a balance is achieved. Moreover, according to the results of this review we know that there is an interaction effect reflected in some physiological features when people are in the combined state of stress with thermal stress and cognitive stress. The same features can be used for the detection of this state with the addition of the BR. This specific feature can be obtained from a breathing band or if one wishes to be less invasive it can be taken from any wearable that measures cardiac output [60], such as many wristbands. According to the personalized classification, apps can be designed to block all kinds of pop ups and notifications that can distract the worker when he is concentrating on a task. Or in case of a very high stress level, an app can be created that sends alerts to the worker and recommends him to stop the task and propose activities that minimize his stress, according to whether he is more stressed by a mental activity or by the thermal environment. These interactive technologies would be designed not only to increase the productivity of companies but also to ensure the well-being of workers within them.

5.2 Education context

In school environments, there is a relationship between the quality of the classroom environment and the mental and physical health of students and their academic performance [12]. Although school settings may be similar to those of an office job, interactive technologies may vary due to different requirements for working with children. Starting with the acquisition methods, children are more active than adults; they are not in an office sitting all the time, they have spaces such as recess, sports classes and didactic games where they are in constant movement. Hence, the sensors have to be as less invasive as possible and appropriate to their daily activity. Body temperature sensors could be integrated into the same wristband that measures heart rate. On the other hand, the physiological indicators evaluated in this review were taken from adult populations, so it would be necessary to study their behavior in children before taking them to a machine learning classifier. Interactive technologies should also be designed according to these young end-users. If children are going to receive personalized feedback of their stress state on tablets or computers, the applications should be intuitive and unobtrusive. For example, if a child's stress level is very high when performing an activity, the child can be shown a slow breathing sequence to regulate the stress without generating a significant stimulus that distracts from the task. But if the technologies are going to be applied by teachers, they can collect information in the cloud and have a wide variety of applications because they have information on the children's stress state and know what times of the day are most stressful for them. In a school day, children are exposed to different subjects that can generate different levels of cognitive demands and consequently different levels of stress states. From there, technologies can be developed in schools to raise comfortable environments that fit the cognitive demands presented to children.

5.3 Health context

In the context of health, these indicators could have a variety of uses. Heat stress can result in heat stroke, heat cramps, among others [61], but it is not given the importance it deserves because people get used to the environments in which they work or live. One of the applications that could impact the health sector is an interconnected system that contributes to telemedicine. By performing, for example, ambulatory tests such as a holter-exam (portable electrocardiogram), doctors could have access not only to the raw electrocardiographic signal at the end of the exam but also to the data being updated continuously in the cell phones and in the databases where the medical records are stored. In case of diagnosis of a person who works in a hot or cold place, the information sent by this device can be analyzed in the cloud, and the device can send notifications to the doctor showing that this may be a reason for the stress causes. One of the significant advantages, why these technologies should be designed for is that they can improve diagnosis from physiological signals [62]. The processing of machine learning algorithms on physiological signals can detect states of people that doctors cannot see by just analyzing the visible changes in the signals.

5.4 Future work: Realization of the Use Scenarios

The temperature control systems proposed to be developed could work in countries with changing seasons and climates as well as in tropical countries since the system is not based on the ambient temperature of the places but on the comfort of the users based on their physiology. Even so, before designing any interactive technology based on physiological signals, it should be taken into account that this may lead to some ethical, political and economic dilemmas.

All systems that require sensors, internet connection, interactive platforms require an economical expense [63] that can be considered high depending on the context. For example, public schools may not have the extra resources to invest in such customized temperature regulation technologies. However, the opposite may be the case in large corporate office contexts if it is demonstrated that productivity gains are considerably high with the use of the technology. On the other hand, at the same time that these technologies are advancing, legislation must advance in different countries to regulate the use of data. The acquisition of physiological signals carries a risk of loss of privacy [64] since physiological data are constantly being stored, and companies and governments can access them. The analysis of these data and identifying states in people can lead to the manipulation of situations and people as their day-to-day changes are known. Therefore, parallel to developing these technologies, applications should be studied and designed, taking into account the threats to privacy, security and ethics that they may bring with them [65].

Finally, the technologies to be designed require much more work because the scenarios within the contexts may vary. Some jobs are considered office jobs where workers sit all day in front of a computer, and there, systems installed with sensors on the computer screens can work. But other people work in factories for example, where the sensors must be designed to work in these environments and appropriate to the activities of people. Also, in these places, people can be exposed to other types of stress such as physical stress, and this should be characterized separately to be able to detect it, as well as other office jobs require public speaking, working in teams, which can produce psychological stress, and this should be characterized as well.

To summarize, we identified which characteristics of the physiological signals could be potential indicators for the differentiation of moderate thermal stress states and the combined stress state (cognitive and thermal), which could not, and which need more research to make reliable conclusions. One of the main challenges of affective computing is enabling computers to interact with users in ways relevant to their affective states [3]. The indicators reviewed are part of the affect recognition, in this case of the stress state. This part of the system's design is based on the physiological features found that serve as inputs for machine learning algorithms, such as Bayesian classifiers, neural networks, and fuzzy systems that can classify stress states and, after processed, give an opportune response, indication, or instruction. To the extent that a machine can detect a person's state, it can adapt its behavior to reduce that person's stress levels. This review opens up opportunities to:

- Investigate the effect on physiological signals caused by the other stress states, i.e., combination of different Ts and different types and levels of cognitive loads.
- Research the multidirectional relationship between different temperatures and their effect on cognitive performance and physiological responses, contributing to identifying inputs for a stress state recognition system.
- Initiate the development of models and systems for classifying stress states.
- Design interactive technologies based on these features for different scenarios in different contexts (education, work, health).

6 CONCLUSION

According to the papers reviewed and analyzed, it can be concluded that the states of stress when a person is subjected to different moderate thermal and cognitive stressors can be reflected in the physiological response of the body. The most promising physiological indicators for identifying a moderate thermal state of stress are body T, LF/HF, and HR. For the identification of the combined stress state, BR can be added to the indicators mentioned above. To enhance human-computer interaction, the machine must have a similar affective recognition as the person to generate a better interaction between the two. The features found in this research can contribute to this interaction, as there is now more information through which machines can identify some human stress states. However, further analysis must be done on physiological indicators caused by different stressors independently and their combination to adjust the physiological features particular to each stress state. Furthermore, challenges for realizing the sensor-based automatic stress detection need to be investigated systematically, thereby identifying cost-effective approaches to overcome them.

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