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SIMULATING HUMAN SENSES TO IMPROVE THERMAL COMFORT

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Abstract

Between the synergies of environmental perception and technological advancement evolves the parallel world of the metaverse. Evolutionary virtuality intends to aid humanity in envisioning the threatened future of cities under environmental risks through tailored features. Traditionally, the sense of sight – which is the focus of virtual reality – has dominated the architectural practice. However, architects and urban designers have begun incorporating other senses into their work over the recent decade. The expanding understanding of the multimodal nature of the human mind that has evolved from cognitive neuroscience research has received little attention so far in the architecture field. This paper investigates the role of synthesized sensory experiences – such as visual, auditory, olfactory, gustatory, and thermal sensations – in designing revolutionary settings that aim to improve people's interactions with their surrounding environments. A 15-minute experiment of an immersive experience in an office setting using virtual reality headsets is utilized to explore the role of multimodal sensory integration towards tolerance to the thermal environment. The findings revealed significant potential in using multiple senses – especially gustatory – to design thermally comfortable spaces. It is hoped that architectural design practice would progressively include our developing understanding of human senses and how they interact. This holistic approach ought to lead to the development of multisensory-inclusive workspaces that promote rather than hinder our social, cognitive, and emotional development.

Keywords

Multisensory; Thermal Perception; Virtual Reality.

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ABSTRACT

Between the synergies of environmental perception and technological advancement evolves the parallel world of the metaverse. Evolutionary virtuality intends to aid humanity in envisioning the threatened future of cities under environmental risks through tailored features. Traditionally, the sense of sight – which is the focus of virtual reality – has dominated the architectural practice. However, architects and urban designers have begun incorporating other senses into their work over the recent decade. The expanding understanding of the multimodal nature of the human mind that has evolved from cognitive neuroscience research has received little attention so far in the architecture field. This paper investigates the role of synthesized sensory experiences – such as visual, auditory, olfactory, gustatory, and thermal sensations – in designing revolutionary settings that aim to improve people's interactions with their surrounding environments. A 15-minute experiment of an immersive experience in an office setting using virtual reality headsets is utilized to explore the role of multimodal sensory integration towards tolerance to the thermal environment. The findings revealed significant potential in using multiple senses – especially gustatory – to design thermally comfortable spaces. It is hoped that architectural design practice would progressively include our developing understanding of human senses and how they interact. This holistic approach ought to lead to the development of multisensory-inclusive workspaces that promote rather than hinder our social, cognitive, and emotional development.

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ملخص

بين تآزر الإدراك البيئي والتقدم التكنولوجي يتطور العالم الموازي للميتافيرس. تهدف الافتراضية التطورية إلى مساعدة البشرية في تصور مستقبل مهدد للمدن من المخاطر البيئية من خلال معاييرهم المفصلة. سيطرت حاسة البصر – والتي هي محور الواقع الافتراضي - على الممارسة المعمارية. وعلى الرغم من ذلك، في العقود الأخيرة، بدأ المعماريون والمصممون في دمج الحواس الأخرى في أعمالهم. وعلى الرغم من تطور أبحاث علم الأعصاب الإدراكي، لم يحظ الفهم الموسع للطبيعة متعددة الوسائط للعقل البشري باهتمام كبير في الآونة الاخيرة. لذلك يتناول موضوع البحث استكشاف تأثير الحواس الفردية - مثل البصر، السمع، الشم، التذوق بالإضافة الى الإحساس الحراري - في تصميم بيئات جديدة تؤدي الي تفاعلات صحية بين الأفراد ومحيطهم. يعرض البحث نتائج تجربة استخدام الواقع الافتراضي متعدد الحواس في بيئة مكتبية على تحسين الإدراك الحسي الحراري. أثبتت نتائج التجربة فعالية تعدد الحواس على الراحة الحرارية للأفراد في الفراغات وتشجيع استخدامها في التصميم. ولذلك نأمل أن تتضمن ممارسات التصميم المعماري للحواس البشرية وكيفية تفاعلها سوياً تطوراً ملحوظاً. حيث يؤدي هذا النهج إلى تطوير فراغات مكتبية ذات تصميم متعدد حواس ليعزز تطورنا الاجتماعي والمعرفي والعاطفي بدلاً من إعاقته.

الكلمات المفتاحية: تعددية الحواس، الإدراك الحسي الحراري، الواقع الافتراضي.

1. INTRODUCTION

Human beings are mostly considered visually dominant creatures (Hutmacher, 2019; Levin, 1993; Posner, Nissen, & Klein, 1976). Therefore, we strongly prefer visual thinking, reasoning, and imagination. Architects have traditionally been no different in this regard, designing mainly for the sense of sight (Bille & Sørensen, 2018; Rybczynski, 2001; Williams, 1980), as Pallasma (1996) noted in his work *The eyes of the skin: Architecture and the senses*. He also stated that our time's architecture is evolving into retinal art for the eyes. Architecture as a whole has devolved into a printed picture art, fixed by the camera's rushed eye. In addition, Le Corbusier (1991, p. 83) – the famous Swiss architect – took it even further, writing, "I exist in life only if I can see." Canadian designer Bruce Mau (2018) also commented on the current predicament that we let only two senses dominate our designs: sound and sight.

Visual dominance can be explained or accounted for at least neuro-scientifically (Hutmacher, 2019; Meijer, Veseli, Calafiore, & Noppeney, 2019). After all, it turns out that processing what we see takes up significantly more of our brains than dealing with information from our other senses (Gallace, Ngo, Sulaitis, & Spence, 2012). According to Felleman and Van Essen (1991), visual information is processed by more than half of the cortex. Others believe the figure is closer to one-third (Eberhard, 2007, p. 49; Palmer, 1999, p. 24). This figure contrasts with the fact that around 12% of the cortex is dedicated to touching, 3% to hearing, and less than 1% to the chemical senses of smell and taste (Spence, 2020). It is worth noting, however, that the denigration of humans' sense of smell, which may be found, for example, in older publications on advertising (Lucas & Britt, 1950), turns out to be founded on dubious foundations. According to McGann (2017) in Science, the dismissal of olfaction dates back to the 1880s, when early French neuroanatomist Paul Broca wanted to make more space in the frontal sections of the brain (i.e., the frontal lobes) for free will. In order to accomplish so, he appears to have had to shrink the olfactory cortex correspondingly. Zimmerman (1989), for example, arrived at a similar hierarchy, albeit with somewhat different weightings for each of the five basic senses. Zimmermann calculated a channel capacity of 10^7 bits/s for vision, 10^6 bits/s for touch, 10^5 bits/s for hearing and olfaction, and 10^3 bits/s for taste (gustation).

Morton Heilig, the creator of the Sensorama – the world's first multisensory virtual reality equipment (Heilig, 1962) – envisioned the hierarchy of attentional capture by each of the senses when writing about the multisensory future of cinema in an article initially published in 1955. Nonetheless, while observers from various disciplines appear to concur on vision's current supremacy, one cannot help but ask what has been lost due to the visual dominance seen everywhere in architecture. Even with the rise of virtual reality, the utilization of its benefits focused on its visual immersion. Chinazzo et al. (2017) used virtual reality to control the virtual conditions to understand the effect of short exposure to colored light on thermal perception. Salamone et al. (2020) evaluated the effect of visual stimuli on thermal comfort using VR techniques. They concluded that the light color has to be considered when predicting the thermal perception of individuals, which is highly due to the focus on visual immersion in VR. While visual hegemony is a phenomenon that can be found in almost every part of our everyday lives (Levin, 1993), the fact that it is so widespread does not mean that its supremacy should not be questioned (Dunn, 2017; Hutmacher, 2019). "Spaces, places, and buildings are clearly encountered as multimodal lived experiences," writes Finnish theorist Pallasmaa (2011, p. 595). We monitor our surroundings with our ears, skin, nose, and tongue rather than registering architecture solely as visual representations. "Architecture is the art of reconciliation between ourselves and the world, and this mediation takes place through the senses," he writes elsewhere (Pallasmaa, 1996, p. 50).

After some studies found cross-effects between multiple comfort domains (i.e., thermal, visual, acoustic, and air quality), the approach to analyzing human comfort has shifted to a multi-domain paradigm (Schweiker et al., 2020). Balcer et al. (2014) proved the effect of multisensory on thermal perception when they explored the integration between the temperature and color of an object, primarily when a conflict arises. According to their findings, participants judged cold temperature feelings as warmer when presented with a visual red color signal and warm temperature sensations cooler when presented with a visual blue color cue. The hue heathypothesis (HHH) (Bennett & Rey, 1972), which proposes that colors influence people's subjective thermal experience, is another example of the interplay between visual and thermal domains.

Moreover, climate change has emerged as a significant area of study in the natural and medical sciences, as well as more recently in the social and political sciences, as a result of the well-documented phenomenon of global warming (Marx et al., 2021). The scientific community has made significant contributions to our understanding of the earth's climate system, including a variety of data and estimates on the future climate as well as information on the implications and dangers of predicted global warming (IPCC 2014; NCA4 2018). In recent decades, climate change has also grown in importance as a political, economic, and environmental concern, as well as a prominent topic of discussion in both public and political discourse.

Due to the heat rise risks we are facing because of climate change, and since the effect of other senses on thermal comfort has not been studied in the workspaces to the best of our knowledge, this paper aims to assess the influence of multisensory experience on the human's thermal perception and comfort level, utilizing the latest-available VR technology: Oculus Quest 2. The significance of this research lies in understanding the influence of other sensory experiences to improve the thermal acceptance of the surrounding environments to cope with heat rise, and hence, design resilient office buildings.

2. METHODOLOGY

2.1. Participants

Participants were recruited from an office space with a targeted age between 23 and 45. A summary of the subjects' main demographic and anthropometric characteristics is listed in Table 1. The experiment was voluntary, and participants were informed that they could withdraw their participation without giving a reason, per the European General Data Protection Regulation's principles and guidelines (GDPR). Prior to participating, the participants were given a printed information letter and asked to sign a consent form. It includes information on data security procedures as well as a generic questionnaire and assessment information. It did not, however, educate the subjects about specific changes in environmental variables, such as temperature changes or the introduction of scents.

Table 1: Demographic and anthropometric characteristics of participants.

Gender	Number	Age Range (Mean)	Height Range in cm (Mean)	Weight in kg (Mean)
Male	1	29 (29)	186 (186)	90 (90)
Female	5	24 – 40 (31)	156 – 167 (163.4)	50 – 70 (59.60)
Total	6	24 – 40 (30.67)	156 – 186 (167.17)	50 – 90 (64.67)

2.2. The Physical And Virtual Set-Up

The experiment was carried out during the month of June 2022 in controlled chambers within a typical office space in Cairo, Egypt. Participants moved between two chambers during the whole experiment. The first chamber was only used to calibrate their thermal sensation by spending 30 minutes seated while doing their work on a PC. The second chamber, the experimental room, is where the immersive sensory testing was conducted using VR Oculus Quest 2 headsets. This chamber is used for lunch/coffee breaks: an exemplar of a lounge in a typical office environment. The space with dimensions of 5.40 x 4.20 x 2.35 m in height (Fig. 1) is lit by office panel lighting and natural lighting from a northeast-facing window with a window-to-wall ratio of 0.25.

Fig.1: Experimental Room (Camber 2): used to conduct the immersive experience.

A split HVAC system kept the first and second rooms at 22 ^{o} C and 32 ^{o} C, respectively. The air temperature for the first chamber set-point air temperature (Ta) of 22.0 ± 1.0 ◦C was defined in accordance with the average HVAC set temperature in the tested office. Relative humidity (RH) was kept at 45 %, and wind speed (V) was almost 0 m/s during the whole experiment. The second chamber Ta was set to 32 ^{o}C, RH was 55 %, V 0 m/s, which exceeds the rate of air temperature changes described in ASHRAE 55. A Testo 410-2 hand-held tool was used to measure and maintain the thermal environments per experiment values.

The three-dimensional virtual model was a built-in template on oculus homes called Retrowave Estate developed by Alphasia_CM (Figure 2). The model consisted of both outdoor and indoor spaces in its essence, which is the case with most office buildings. The violet and black colors were dominant in the outdoor spaces, and black with cyan strips for the indoor ones. The model could be used to demonstrate office environments in the future of the metaverse, where scenes are not constrained by physical boundaries such as that in the real world. The environment included a multilevel skeleton structure open to the surrounding views.

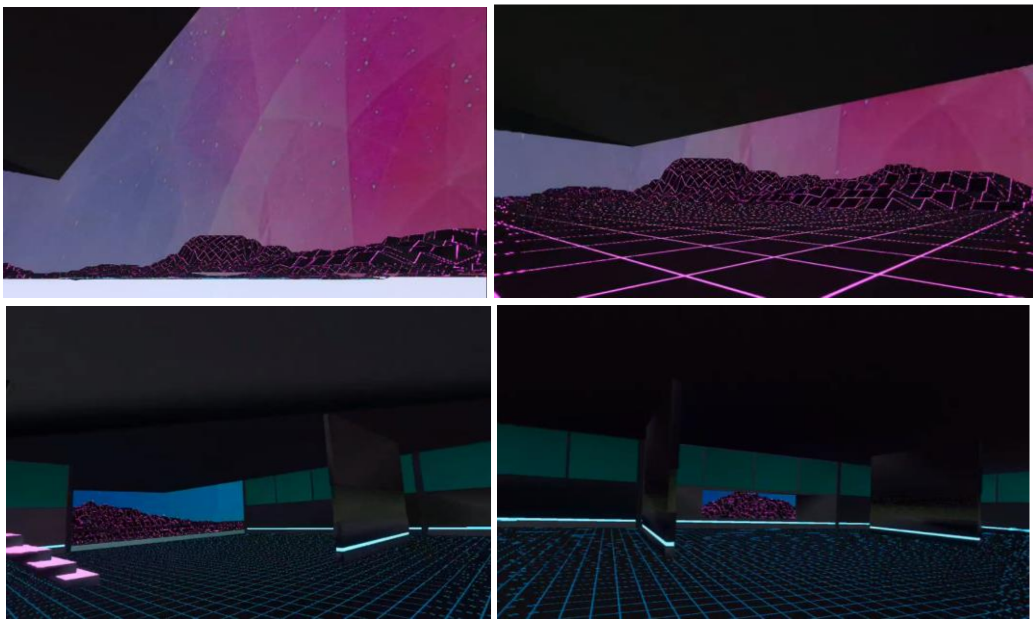

Fig.2: Virtual Set-Up: the immersive visual environment (visual stimulus).

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2.3. Experiment

The experiment lasted 10 minutes to maintain heat dissipation from the VR headset (Wang et al., 2018). The influence of the induced sensory stimuli was recorded three times during the experiment. 1) When they entered the experiment chamber before wearing the VR headset where the thermal environment was the only stimulus. 2) After two minutes from wearing the headset. The visual stimulus was added to the previous thermal stimulus. 3) After inducing all stimuli; olfactory, gustatory, and auditory (Figure 3). Votes for rating all the five senses included in the experiment were collected in the following format.

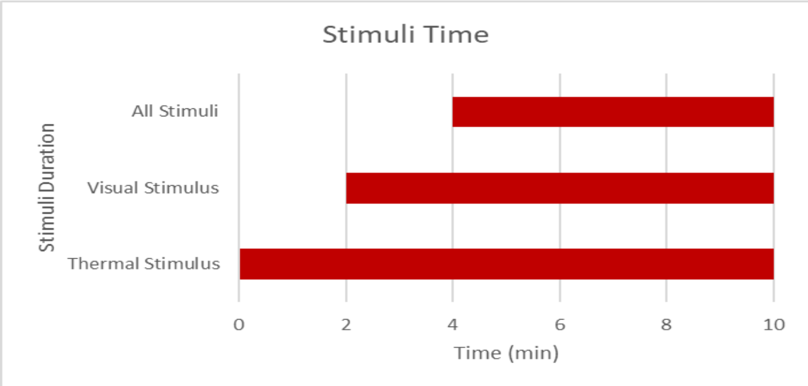

Fig.3: Stimuli Introduction Time and Duration.

Each participant was experimented individually, following identical procedures. Each person spent 30 minutes seated while working on a PC in the first chamber under the thermal conditions stated earlier. The participant then moved to the experiment room, which was 10 ^{o}C warmer in terms of air temperature. Thermal sensation votes (TSV) and thermal comfort votes (TCV) were collected. We used a Likert-type scoring method from the participants to rate these two votes. The thermal sensation votes (TSV) used a 7-scale ASHRAE standard (1- Cold 2- Cool 3- Slightly Cool 4- Neutral 5- Slightly Warm 6- Warm 7- Hot). Thermal comfort votes (TCV), on the other hand, ranged from 1 to 5 (1- Extremely Uncomfortable 2- Uncomfortable 3- Neutral 4- Comfortable 5- Extremely Comfortable). The participants wore VR headsets, which introduced the 3D visual environment demonstrated earlier, and were free to explore and navigate using two hand-held controllers. The gustatory stimulus was introduced through a cold orange juice drink, which is known to regulate perceived thermal comfort. The auditory stimulus used *Miserere, Allegri* music, which has proven to mitigate stress response (Thoma et al., 2013). The olfactory stimulus was introduced through Citrus and Lavender scents, also known for reducing stress and helping meditation during aromatherapy (Cauchi, 2021). It is worth mentioning that the former three stimuli were introduced simultaneously. The experiment procedures are further illustrated in Figure 4. Records of the TSV and TCV were collected each time. Enough time was given for each participant to explore the immersive environment before ending the experiment. After removing the VR headsets, participants were asked to explain their overall experience and preferences and identify the most effective stimulus.

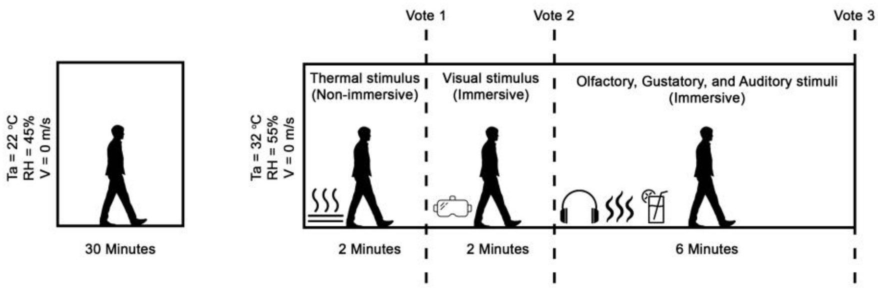

Fig.4: Experiment Procedures.

The participants' olfactory, gustatory, and auditory sensory votes used a five-step Likert-type scale to rate their intensity, where '1' was insignificant and '5' was very intense. The goal was to verify the influence of an integrated sensory experience to improve thermal comfort and increase people's tolerance to heat.

3. RESULTS

The thermal sensation votes were used to identify the participants' thermal perception of their thermal environment. First, we tested the results' normality for thermal sensation (TS) and thermal comfort (TC) using the Shapiro–Wilk test. The results are shown in Table 2.

Table 2: Shapiro-Wilk test results to show the distribution of the different votes

		TS (Thermal Stimulus)	TS (Visual Stimulus)	TS (All Stimuli)	TC (Thermal Stimulus)	TC (Visual Stimulus)	TC (All Stimuli)
Shapiro-Wilk	P value	0.240	0.0104**	0.047**	0.005***	0.494	0.005***
**p < 0.05, ***p < 0.01							

Most distributions show a significant departure from normality as the p-value is less than 0.05, so we concluded that the distributions are not normal. Second, we analyzed the thermal sensation and thermal comfort during the three stages indicated in the methodology using the Mann-Whitney U Test to see if there were considerable variations between the three sets of results (Tables 3 and 4).

Table 3: Mann-Whitney U Test Results for Thermal Sensation

		TS (Thermal Stimulus)	TS (Visual Stimulus)	TS (All Stimuli)
TS (Thermal Stimulus)	U-value P-value	-		
TS (Visual Stimulus)	U-value P-value	9 0.17384	-	
TS (All Stimuli)	U-value P-value	11.5 0.33706	4.5 0.03752**	-
** p < 0.05				

Table 4. Mann-Whitney U Test Results for Thermal Comfort

		TC (Thermal Stimulus)	TC (Visual Stimulus)	TC (All Stimuli)
TC (Thermal Stimulus)	U-value P-value	-		
TC (Visual Stimulus)	U-value P-value	12 0.37886	-	
TC (All Stimuli)	U-value P-value	8 0.12852	7 0.09296*	-
*p < 0.10				

As the p-value comparing different thermal comfort and sensation votes is only less than 0.10 when comparing visual stimulus to all stimuli, it is concluded that the results show no significant difference between the different data sets except between the 'visual stimulus' and

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the 'all stimuli' in both the thermal sensation and thermal comfort. However, the boxplots (Figures 5 and 6) show considerable variations between the three sets.

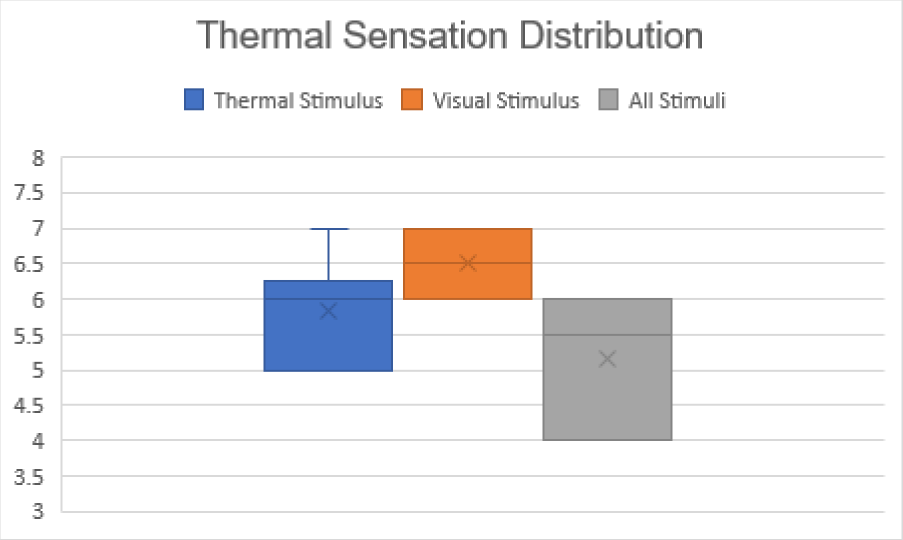

Fig.5: Boxplot for Thermal Sensation.

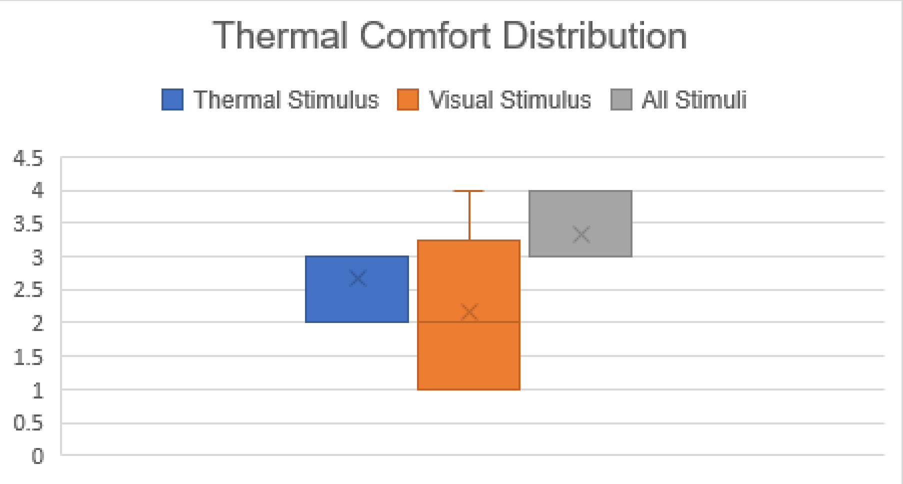

Fig.6: Boxplot for Thermal Comfort.

For both thermal sensation and thermal comfort, the mean value got worse from the first set (thermal stimulus) to the second one (visual stimulus). This observation does not necessarily mean the visual stimulus negatively affects those parameters because the heat accumulation during the first two minutes can result in the same outcome. The results only mean that the visual stimulus cannot withstand the accumulation of heat on its own. Later, after the integration of other sensory, 'all stimuli' parameter, a considerable, positive impact on TSV and TCV were recorded. For the thermal perception, the 'all stimuli' showed an improvement in the thermal sensation – towards comfort levels – with a mean value of 5.167 compared to 5.833 and 6.5 for 'thermal stimulus' and 'visual stimulus,' respectively. It also showed an improvement in the thermal comfort level with a mean value of 3.333, compared to 2.667 and 2.167 for 'thermal stimulus' and 'visual stimulus,' respectively. It is also worth mentioning that after introducing the multisensory stimuli, the participants rated the intensity of the gustatory sense the highest, with an average of 4.333 out of 5, followed by the auditory sense with an average of 4.167. Surprisingly the visual sense scored the lowest along with the olfactory sense with an average of 3.5.

4. DISCUSSION

The findings validate the influence of the multisensory stimuli on improving the individuals' thermal sensation, which was not observed through the visual stimulus alone as the mean of the comfort vote increased and the thermal sensation vote decreased, which are both preferable in the experiment context. We suspect that the reduced influence of the visual stimulus compared to the other stimuli on the thermal tolerance could be due to the expectations of the subjects moving into the immersive space during the first transition. The psychological factor –the expectations in this context – strongly influences the thermal sensation vote, which is reflected in the numbers stated above. The introduction of all stimuli during the immersive stage of the experiment had amplified effects. However, further experiments are needed to verify these findings in which other stimuli are introduced prior to the visual stimulus. All the votes recorded revealed improved thermal comfort levels with higher tolerance to the warmer conditions of the space when all senses were induced. After removing their VR headsets and during their post-experiment interview, participants ensured such findings. The intensity of each sense was recorded by the participants and ranked accordingly. The Gustatory was ranked first, followed by the auditory. The visual and olfactory were tied for the lowest ranking.

The results validated the influence of *Miserere, Allegri* music to mitigate stress response (Thoma et al., 2013) and improve the thermal tolerance of individuals. Other types of music could be tested further in future work. In addition, the evaluation of the lavender versus citrus scents revealed that lavender is better in elevating comfort and improving thermal sensation. The effects of lavender in reducing stress have been proved by Cauchi (2021), which further confirms our findings.

The technological advancements allowed us to utilize virtual reality environments to control the sense of sight without compromising the control of the other senses, which opens up the possibility of investigating different environmental conditions in different settings and understanding the effect of each on our thermal sensation and thermal comfort. Many studies concluded that humans spend an average of 87% of their time indoors (Diffey, 2010). This figure has potentially increased in the last couple of years due to the COVID-19 pandemic and the emergence of remote or hybrid work models. This phenomenon leads to improving and integrating virtual reality settings in workspaces. It is hoped that the findings of this research encourage professionals to design and develop spaces for such emerging models using multisensory stimuli as their main driving force for better accommodation of comfort in mitigating the heat rise of cities. As the results provide first insights into the effect of the multisensory experiences, future investigations into this matter are encouraged.

5. CONCLUSION AND FUTURE RECOMMENDATIONS

This study acts as a proof-of-concept for the effect of multisensory stimuli on thermal sensation and thermal comfort to mitigate heat rise risks due to climate change. In order for architects to develop an understanding of those effects, it is imperative for future study designs to address different types for each stimulus, similar to our test for citrus versus lavender scents. Cross-referencing different variations of the different senses shall allow future studies to reach more insightful results.

Our statistical methods for testing the normality of the results and variance significance using Shapiro-Wilk and Mann-Whitney U tests, respectively, are designed for a small sample of data and nonparametric sets. However, in future studies, with the increase in participants number, we recommend using the Kolmogorov-Smirnov test for normality, and if it yielded a normal distribution of results, the use of the T-test would be recommended instead of Mann-Whitney. Finally, in addition to the statistical approach, we recommend intensive investigation of the gustatory sense since it showed the greatest potential in improving thermal comfort, and participants rated its intensity the highest.

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