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Using laboratory experiment to inform local adaptation policies for extreme heat events

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ABSTRACT

Issuing early heat warnings and enhancing public climate change awareness and engagement are important local policy options for heat wave adaptation. Here, we used a laboratory experiment to inform major gaps in making these two policies, including setting proper thresholds for heat alerting systems and figuring out how heat experience shifts individuals' climate change perceptions. Taking Nanjing as a case city, we simulated a heat event by increasing temperature from 25 °C to 40 °C (70% relative humidity) in a climate chamber and recruited 58 young adults as participants. Physical thermal responses, including skin temperature and heart rate variability, were recorded using portable devices. Subjective thermal perceptions, climate change belief and psychological distance were measured by self-rated scales before, during, and after the exposure. We found physiological responses were correlated with subjective thermal perceptions and showed sharp rises from 30° to 35°C, presenting aggravated thermal discomfort. Moreover, heat exposure increased climate change belief and reduced psychological distance significantly. After the experiment, follow-up surveys showed participants had a short memory of the heat exposure, but daily temperature variations still predicted climate change belief. The findings suggest in our case city, the current threshold (35 °C) for heat warnings may not be safe enough. Local authorities should consider prolonged periods of hot weather with temperature between 30 and 35 °C. Due to strong links between heat experience and climate change perceptions, we encourage to take this "window of opportunity" when heat events occur to communicate climate risks and enact post-event policy changes.

1. Introduction

Extreme heat events jeopardize the well-being of people and are responsible for a large number of deaths and economic losses around the globe (Zhu et al., 2021). In 2003, the unprecedented heat event in France resulted in ~15 000 excess deaths (Dhainaut et al., 2004). The 2010 Russian heatwave killed over 50 000 people, with more than 15 billion US$ in economic losses (Rasmijn et al., 2018). In China, 2.7% of non-accidental deaths in 2013–15 might be attributed to heat exposure (Chen et al., 2018). The adverse effect of extreme heat events is influenced by environmental and sociodemographic determinants, including personal acclimatization to the local climate, the spread of air conditioning, and access to health care systems (Alkemade et al., 2021). Climate change will continuously increase the frequency, duration, and intensity of extreme heat events (Perkins-Kirkpatrick and Lewis, 2020). To reduce heat-related morbidity and mortality, developing local adaptation strategies and effective intervention measures should be listed as a public health priority (Giordono et al., 2020).

Local governments have adopted and implemented a range of adaptation policies in response to extreme heat events. Among them, establishing a public alerting system before and during persistent hot weather conditions has been recognized as one of the most important ways to reduce heat-related health risks (Turek-Hankins et al., 2021). An effective alerting system will arouse public attention for self-protection and activate intervention measures from local health authorities. The determination of a proper threshold that triggers the issuance of heat warning messages when forecasted or reached is critical for an alerting system (Di Napoli et al., 2019). There are no universal indexes and thresholds used uniformly across countries and regions. For example, in the United States, Heat Index (HI) values calculated based on air temperature and relative humidity, are used for the issuance of Heat Advisory (daytime highs 37–40 ℃), Excessive Heat Warning (daytime highs

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40–43 ℃), and Excessive Heat Watch (daytime highs > 43 ℃) (EPA, U, 2006). French national weather service issues heat warnings when they predict maximum daily temperatures above 33 °C last at least three consecutive days (Casanueva et al., 2019). In China, three levels of heat warnings are officially issued when the daily maximum temperature exceeds 35 °C (3 consecutive days), 37 °C (24 h), and 40 °C (24 h), respectively (Zhang et al., 2017).

Climate researchers and epidemiologists are widely engaged in setting thresholds for heat warning systems. A large body of literature attempts to identify warning thresholds by evaluating the statistical relationships between heat indicators (e.g., wet-bulb globe temperature) and health records (e.g., hospital admissions) (Cheng et al., 2019). Those research efforts emphasize the need to adjust thresholds according to local climatic conditions as well as the degree of the populations' vulnerability and physiological acclimatization (Folkerts et al., 2020). However, health outcomes adopted in these studies neglect physiological responses to a sudden rise in temperature, such as declined heart rate variability, which reflects the thermoregulation process and are directly linked to some acute health outcomes (Hanna and Tait, 2015). In addition, subjective heat stress, such as thermal comfort and thermal acceptability, is related to individuals' motivation to adapt and work productivity. These subjective indicators have also rarely been considered in setting thresholds for warning systems (Beckmann et al., 2021). Moreover, there may be a lack of complete mortality and morbidity records datasets in resource-scarce developing countries or regions to build local heat-health relationships. To help local authorities set proper thresholds for heat warning systems, there is a need to seek efficient approaches that provide insights into the effects of extreme heat events on local residents' physiology and subjective wellbeing.

Another important policy option in response to heat waves is raising public awareness of climate change risks and promoting longer-term adaptation initiatives. Climate change perception plays a crucial role in shaping individual and societal responses to the climate crisis (Barnes et al., 2020). By discounting the risks and threats associated with climate change, some individuals and communities are rendered vulnerable because they choose not to take the necessary steps to adapt. However, humans find it more difficult to make sense of climate change because of its global scale, uncertainty, and intangibility (Leviston et al., 2014). In reality, people often rely on personal experiences with weather abnormality or extreme weather events to perceive climate change (Dai et al., 2015; Ray et al., 2017). Extreme heat is also known as one of the climate disasters that can yield increases in public attention and introduce "windows of opportunity" for communicating climate risks, influencing public discourses, and enacting post-event policy change (Giordono et al., 2020).

A number of studies have examined if exposure to extreme heat shifts individuals' climate change beliefs and policy preferences, though results are mixed. Evidence for a "local warming" effect has emerged in recent years, suggesting that elevated temperature in the short term (daily to monthly) is associated with increased concern about climate change (Joireman et al., 2010; Li et al., 2011). For example, Hamilton and Stampone (2013) merged 5000 state-level telephone interview data with temperature indicators. They found the respondents were more likely to agree with the scientific consensus of climate change when interviewed on unseasonably warm days. The association between temperature and climate change perceptions indicated that instant heat experience could reshape public opinion. However, some studies have found little or no effect of temperature experiences on climate change opinion (Deryugina, 2013). A major approach in this area was to join temperature data with georeferenced opinion data and then build a statistical relationship between the two variables. However, this cross-sectional analysis had a limited capacity to identify causal effects (Howe et al., 2019). Moreover, aggregated data could not ensure people in one place had the same temperature exposure, which might cause ecological fallacy (Deryugina, 2013). In this regard, longitudinal studies should be adopted to examine how shifts in climate change perceptions may be associated heat wave events at the individual level.

To address the above challenges, laboratory experiments can help inform policy-makings of early heat warnings/climate communication by simulating a heat wave process and investigating subjects' responses using small sample sizes (Karjalainen, 2012; Rupp et al., 2015; Song et al., 2020). In those heat-exposure lab studies, participants were exposed to different temperatures, and their thermal sensation votes or physiological signals were measured and compared by condition. For example, Liu et al. (2008) exposed 33 subjects to a series of temperature ranging from 21 °C and 30 °C in a climate chamber. They found rising temperature increased uncomfortable feeling and sympathetic activity played a key role in affecting subjects' thermal discomfort. The knowledge of thermal responses and subjective wellbeing during a simulated heat wave event is informative for designing thresholds of heat warning systems in the outside world (Luther et al., 2016).

Moreover, a laboratory experiment is also advantageous in making causal inferences by collecting longitudinal data (Falk and Heckman James, 2009). Participants will receive the same physical exposure, and their climate change perceptions can be measured before and after a simulated extreme heat event. However, very few studies have used experiment to demonstrate the effect of heat wave experience on climate change perceptions. The only lab-based experimental study finds that warmth felt by subjects in a hot room can increase belief in climate change (Risen and Critcher, 2011). We need more experimental evidence to validate the effect of extreme heat experience on climate change perceptions, which is critical for designing effective communication strategies and motivates longer-term post-event adaptation actions.

In this study, we aimed to use laboratory experiments to inform the setting of heat warning thresholds and investigate the impact of extreme heat event on climate change perceptions. The study was conducted in Nanjing, a hot and humid coastal city located in eastern China. The city faces high heat stress risks, with 18 days of highest temperature over 35 °C in 2019 summer and average relative humidity of around 70–75% (Zheng et al., 2021). We recruited a total of 58 healthy college students to attend heat exposure in a climate chamber where temperature steadily increased from 25 °C to 40 °C and relative humidity was kept around 70%. Physiological signals and self-rated thermal perceptions were measured to reflect thermal responses. Climate change belief and psychological distance were measured before, during, and after the heat exposure to replicate the "local warming" effect. In addition, after the experiment, we conducted a series of follow-up questionnaire surveys to track participants' memory of the heat exposure and climate change perceptions at the moment.

Our study answers the following questions. First, how do people physiologically and subjectively respond to a simulated extreme heat event? How does empirical knowledge of human experimentation in heat chambers inform the setting of heat warning thresholds? Second, regarding the "local warming" effect, will extreme heat exposure increase climate change belief and shorten psychological distance? What are the underlying mechanisms? Finally, after the experiment, how do participants recall the short-term heat exposure? Will the "local warming" effect still exist in the absence of extreme temperatures? What are the broader implications for communicating climate change and extreme heat risks?

2. Methods

2.1. Participants and ethics procedure

The study was approved by the Ethics Committee of Jiangsu Provincial Center for Disease Prevention and Control (#JSJK2018-B006–02) and accomplished in a climate chamber in Nanjing, China. We recruited the undergraduate students with payments and excluded those who had cardiovascular or skin medical history, pain conditions, implants, and were pregnant. All participants gave informed written consent before visiting the lab. They were informed that heat exposure process may cause some physical discomfort and they were allowed to leave the research at any time. All data were collected, stored only for research purpose and were analyzed in a way that there would be no identifying information available. If any participant got injured as a result of taking part in the experiment, we would provide medical care immediately.

We calculated a minimum sample size of at least 46, ensuring a power of 90%, a level of significance of 5% (two-sided), and an effect size of 0.5 between pairs. Finally, 58 healthy students (38 females and 20 males; 19.2 ± 0.7 years old) participated in the experiment. These students have lived more than one year in Nanjing and experienced the summer here. Some studies have suggested that individuals' thermal tolerance may be related to their past exposure experience (Cao et al., 2011). According to the locations of these participants' hometowns, we classified them into two groups based on climate zones to test this effect (21 from the North and 37 from the South). See Fig. S1 for geographical distributions and Table S1 for anthropometric information. They were instructed to have an adequate sleep, maintain a regular diet, and avoid strenuous physical activity or taking caffeine, alcohol, and medication 24 h before visiting the lab. Females were instructed to visit the lab after the first week of their menstrual cycle.

2.2. Instruments and measurements

The experiment was conducted in a lab that contained two adjacent microclimate-controlled rooms connected by an internal door (Room A: 3.8 m * 3.6 m * 2.65 m, Room B: 3.8 m * 3.8 m * 2.65 m, see Fig. S2 for the room layout). The rooms allowed for adjustment of the air temperature, relative humidity, and air velocity. Room A was set at 25 °C constantly to represent a baseline temperature level, while Room B was heated from 30° to 40°C (see Fig. 1 for the temperature adjustment procedure). The relative humidity was maintained within 65–70% as the typical Nanjing summer condition. The air velocity was kept under 0.2 m/s (Liu et al., 2017). Climatic variables and air quality index were monitored throughout the experiment. See Table S2 for the descriptions of all apparatus used in the experiment.

Physiological responses including skin temperature and electrocardiogram (ECG) were measured throughout the heat exposure. Skin temperature sensors were attached at seven body parts (forehead, chest, lower arm, back of hand, thigh calf, lower leg, and dorsal foot), which recorded data every 2 min automatically. After the experiment, we exported the raw data and calculated mean body skin temperature (T_{skin}) according to the weights recommended by Ramanathan (1964) as shown in Eq. (1).

$$T_{skin} = 0.07T_{forehead} + 0.35T_{chest} + 0.14T_{lowerarm} + 0.05T_{handback} + 0.19T_{tigh} + 0.13T_{lowerleg} + 0.07T_{dorsalfoot} \tag{1}$$

ECG was monitored by wireless chest strap data loggers with a sampling rate of 250 Hz. After the experiment, raw ECG digital data was imported, cleaned, and analyzed by a python-based heart rate analysis module *HeartPy* (van Gent et al., 2019). Both heart rate (HR) and heart rate variability (HRV) were calculated. HR measured the number of heartbeats per unit of time, and HRV measured the variability between successive heartbeats. HRV was accepted as a non-invasive marker of autonomic nervous system (ANS) activity (Shaffer and Ginsberg, 2017). Time-domain (RMSSD, SDNN, etc.) and frequency domain (LF/HF, etc.) HRV indictors were used. See Table S3 for all HRV measurements used in this study and their meanings. Four continuous voting scales ranging from − 50 to 50 were employed to measure thermal sensation, thermal comfort, thermal acceptability, and air quality acceptability. Larger scores indicated perceiving higher temperature, more comfort, and higher thermal and air quality acceptability. Table S4 describes all the thermal perception scales.

To examine the "local warming" effect of heat exposure on climate change perceptions, we measured participants' climate change belief and psychological distance. For climate change belief, we asked participants: How certain do you believe climate change is happening? A scale of 0–100 indicates "strongly disbelieve" to "strongly believe". For psychological distance, two questions were asked from temporal and geographical dimensions: (1) "When will climate change impacts occur?" and (2) "Will climate change mostly affect my local area or places that are far away from here?" (Spence et al., 2012; Wang et al., 2019). A scale of 0–100 represents "right now / right here" to "in distant future / in distant places". The lower psychological distance of climate change was generally associated with higher levels of concern (Spence et al., 2012). We mixed climate change questions with a set of control questions measuring the perceptions of other social events (college entrance exams, Boeing 737 MAX groundings, and vaccine scandal in China) (specified in Table S5). We expected that the heat exposure should affect only the answers to climate change questions if the "local warming" effect existed. The control questions also helped disguise the true research goals and avoided strong conceptual priming of climate change.

2.3. Experimental design

The experiment was conducted from October to November 2019 and lasted for five weeks. Five participants visited the lab together as a group, and each visit took approximately 3.5 h. Fig. 1 summarizes the experimental procedure. After arrival, participants first stayed in Room A (25 °C). We provided them with uniform clothes (T-shirts, short trousers, and slippers), instructed them to wear the portable ECG recorder, and attached the skin temperature sensors to them. When participants had adapted to the environment and showed stable physiological signals, ECG and skin temperature were recorded for 20 min. Participants were allowed to have sedentary activities such as reading. Thermal perception and climate change perception were surveyed after the physiological signal recording.

Once completing the surveys in Room A, participants entered Room

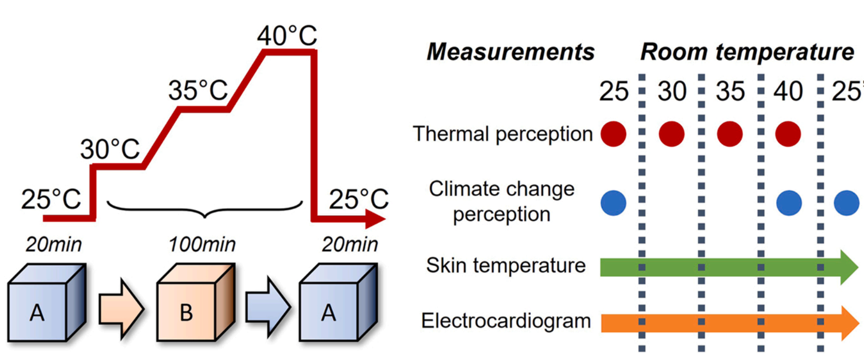

Fig. 1. Experimental procedure and measurements at each phase.

B. Temperature in Room B was increased from 30 °C to 35 °C and 40 °C. Participants stayed 20 min at each temperature phase. The heating process from 30 °C to 35 °C and from 35 °C to 40 °C also took approximately 20 min, respectively. ECG and skin temperature were recorded throughout this session. Participants gave their thermal perception votes at the end of three phases. Climate change perception survey was performed only at the end of the 40 °C phase. Participants spent about 100 min in Room B, and everyone was provided with a bottle of 300 mL water. After finishing all tests in Room B, participants returned to Room A (25 °C) to take the final 20 min physiological recording. Climate change perception was measured again before the end of the whole experiment.

Moreover, to track participants' memory of the heat exposure and climate change perceptions, we conducted four rounds of follow-up surveys via online questionnaires on the 1st, 5th, 15th and 30th day after the experiment. Participants were asked to recall their thermal sensation, thermal comfort, and thermal acceptability at the 40 °C phase and give votes on the same scales used in the experiment. We also asked participants about their current climate change beliefs and psychological distance. When measuring climate change perceptions, participants were reminded that it was not a memory task, and they should give feedback based on their in-the-moment judgments.

2.4. Statistical analysis

To explore physiological and subjective thermal responses, we first examined data distributions by plotting histograms and performing Shapiro-Wilk (S-W) normality test at different temperature conditions. We used ANOVA to compare physiological and subjective indicators between temperature conditions for normally distributed data. We performed non-parametric tests (Friedman test, Wilcoxon signed-rank test) for abnormally distributed data. Gender and geographical background were tested as two between-subject factors.

Next, we performed multilevel correlation and calculated Spearman's rank correlation coefficient (ρ values) between subjective perceptions and physiological signals. Multilevel correlation accounts for the baseline differences between individuals in longitudinal data and was operated based on the *correlation* package in R.

Finally, we applied multilevel modeling (MLMs) to examine the predictors of heat exposure memory and climate change perceptions in the follow-up surveys. The model is specified in Eq. (2).

$$Y_{it} = \beta_0 + \beta_1 Time_i + \beta_2 Max\_Temp_{it} + \beta_3 Min\_Temp_{it} + \beta_4 Gender_i + \beta_5 Geo\_Background_i + \mu_i + \varepsilon_{it} \quad (2)$$

Y_{it} is the dependent variable i.e., the i th subject's responses to questions of heat exposure memory and climate change perception. $Time_i$ is the survey timepoint, i.e., 1st, 5th, 15th and 30th day after the experiment. Max_Temp_{it} and Min_Temp_{it} are two time-varying variables denoting the maximum and minimum temperature on the survey day. $Gender_i$ and $Geo\_Background_i$ are two within-subject factors that denote gender and geographical background of the i th subject. μ_i denotes the random intercept and ε_{it} denotes the error terms. The model was run based on *lme4* package in R.

3. Results and discussions

3.1. Physiological responses and thermal perceptions under the heat

Results showed that temperature significantly influenced HR ($F = 142.3$, $p < 0.001$) and HRV indicators (RMSSD: $\chi^2 = 86.7$, $p < 0.001$; pNN50: $\chi^2 = 96.1$, $p < 0.001$) (Fig. 2 abc). HR exhibited a step-up trend

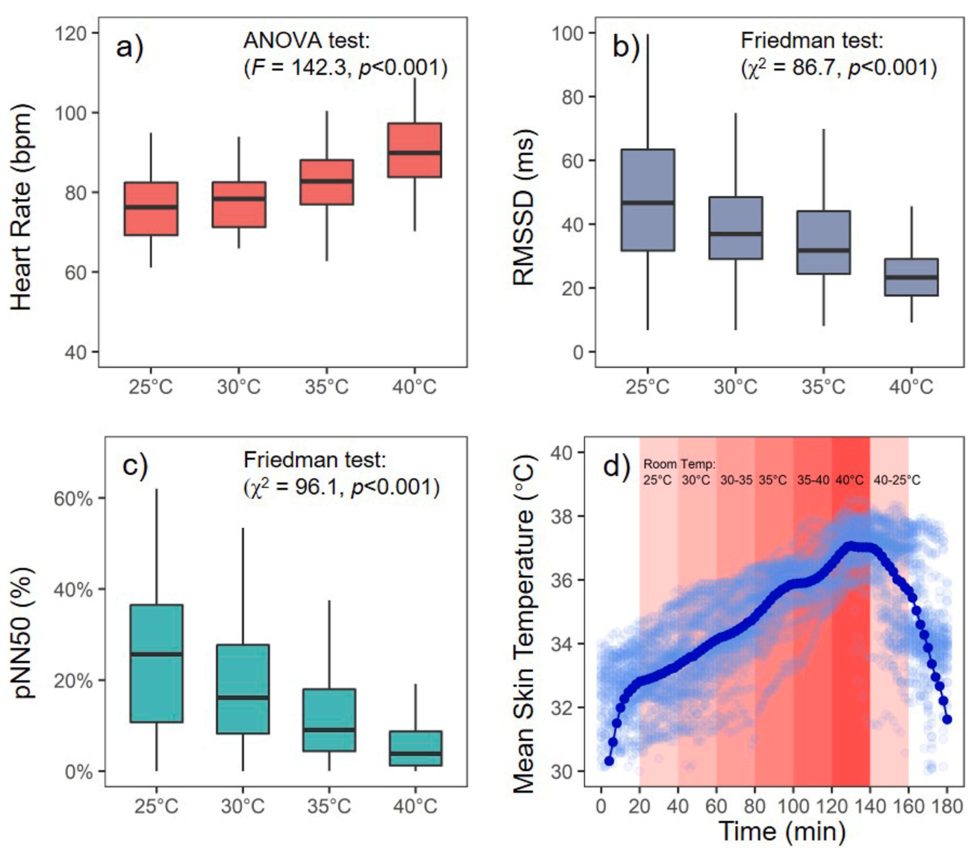

Fig. 2. ECG indicators and mean skin temperature per temperature condition. Boxplots a), b), and c) show the changes of ECG indicators HR, RMSSD, pNN50 per temperature condition. The other HRV indicators are presented in Fig. S3. Scatter plot d) illustrates the mean skin temperature changes over time. Light blue dots show the mean skin temperature for each subject. Linked dark blue dots show the grand average of mean skin temperature for all subjects at each time point.

as temperature increased, indicating more intensive workload on the heart. Two HRV indicators decreased in turn, indicating a decline in autonomic cardiac function under the heat. In addition, HR did not change significantly from 25 °C to 30 °C, whereas HRV indicators showed obvious down-step changes. It indicated HRV indicators respond faster to the thermal stress. Meanwhile, males and subjects from the North had smaller HR and higher HRV indicators but the differences were significant only at a few temperature conditions (Fig. S5). Skin temperature followed a smoothly increasing trend from 33.2 °C (± 1.19) to 37.0 °C (± 0.85) as temperature rose from 25 °C to 40 °C (Fig. 2d). We found no significant effects of gender or geographic background on mean skin temperature (Fig. S6).

As temperature rose from 25 °C to 40 °C, thermal sensation increased from a median of 0 to 40 (Fig. 3a). Thermal sensation had small data variations, which meant participants had consistent judgments of the temperature. Conversely, temperature comfort, acceptability, and air quality acceptability decreased from medians of 22, 25, and 50 to − 34, − 25, and − 15 (Fig. 3bcd). These measurements exhibited larger variations, indicating participants had discrepant thermal preferences and endurance. For temperature comfort and temperature acceptability, the differences between 25 °C and 30 °C conditions were marginal (Wilcoxon signed-rank test $p = 0.069$ and $p = 0.087$, respectively), but there were sharp declines from 30 °C to 35 °C. It implied a potential threshold for thermal comfort between 30 °C and 35 °C. We found no significant effect of gender or geographic background on thermal perceptions (Fig. S7).

Furthermore, physiological signals and subjective perceptions were highly correlated. Taking heart rate (HR) as an example, temperature sensation was positively associated with HR ($\rho = 0.71$, $p < 0.001$) (Fig. 3e). Temperature comfort ($\rho = -0.64$, $p < 0.001$), temperature acceptability ($\rho = -0.54$, $p < 0.001$), and air quality acceptability ($\rho = -0.43$, $p < 0.001$) were negatively correlated with HR, and the relationships were relatively weaker compared to temperature sensation. There were similar regularities between other physiological signals and thermal perceptions (Table S7).

Our experimental evidence suggests that more localized and nuanced thresholds for heat warning systems are required to reduce heat-related health risks. In China, a heatwave is officially defined as a period of at least three consecutive days in which the daily maximum temperature exceeds 35 °C (Zhang et al., 2017). However, an alert threshold at 35 °C may not be safe enough for local practices in Nanjing city. Using the gold standard of cardiac risk (SDNN < 40 ms) (Umetani et al., 1998) as the criteria, we calculated the proportion of participants endangered cardiac risk under different temperature conditions. We found that the heating process from 30 °C to 35 °C increased the proportion of participants who were endangered cardiac health risks significantly (Fig. S8). For local health authorities, the issuance of a local heat warning should consider short-term extreme temperature conditions (e.g., 2 h 40 °C) or sustained periods of hot weather between 30 and 35 °C. Fig. 4.

Our results show that although subjective thermal perception indicators are highly correlated with physiological responses, subjective thermal comfort and acceptability show the most significant decreases from 30 and 35 °C. It implies that a threshold for subjective thermal wellbeing may also exist between 30 °C and 35 °C for most participants, which should be taken into consideration when defining heat warning thresholds. Meanwhile, since subjective thermal perceptions are sensitive to heat and physiological thermal responses, they can be used as good indicators for heat health surveillance and warning issuance. As people search, consume, and share abundant information on the web, the crowdsourced data produced in these processes (e.g., internet searches, social media text corpora) can be processed and utilized as potential sources for tracking public thermal wellbeing and setting thresholds for subjective heat stress.

Our study provides a new experimental paradigm to identify proper thresholds for heat warning systems. Compared to traditional epidemiological approaches, the experimental study in climate chamber measures the impact of heat exposure on physiology and subjective wellbeing directly. These measures reflect thermal acclimatization and

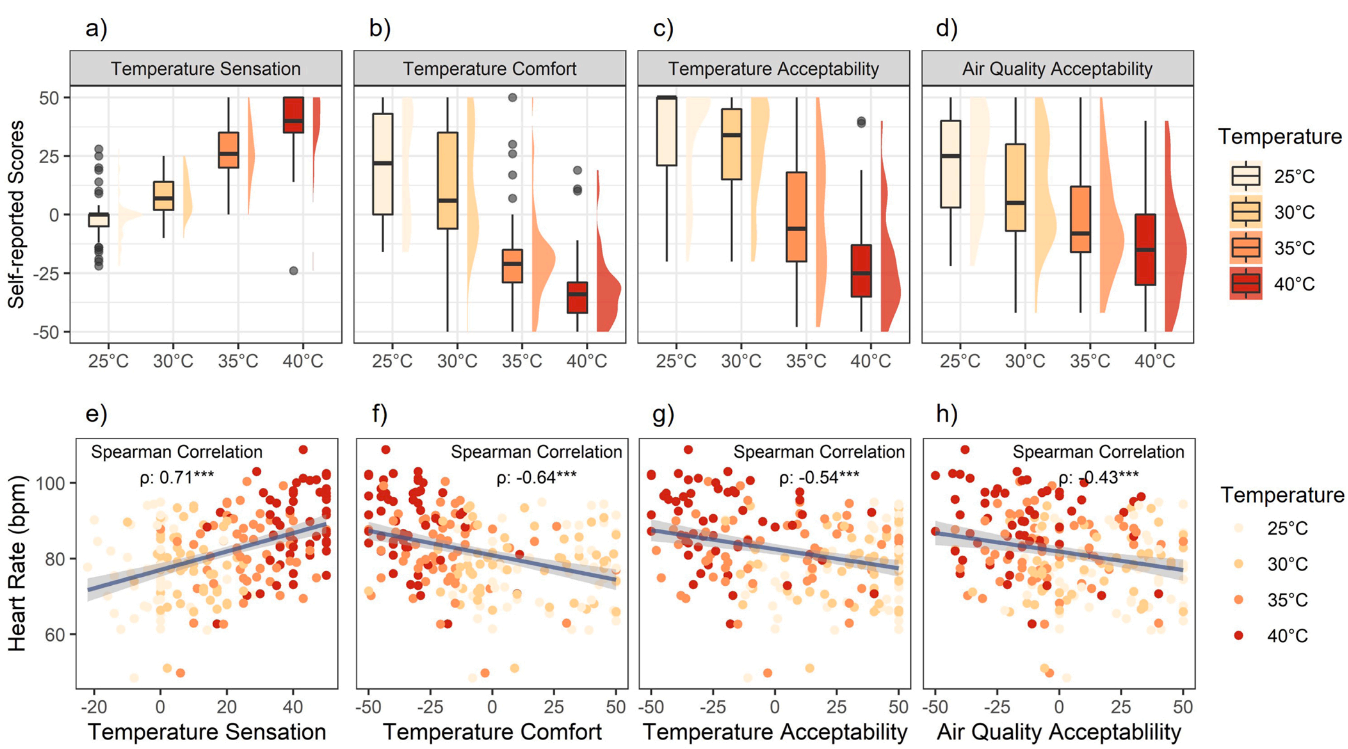

Fig. 3. Subjective thermal perceptions and their correlations with heart rate. Plots a), b), c), and d) depict the data distributions of four subjective thermal perception measures at different temperature conditions. Plots e), f), g), and h) show the correlation between thermal perceptions and heart rate. Spearman's correlation coefficient ρ and its significance are labeled. (*** $p < 0.001$).

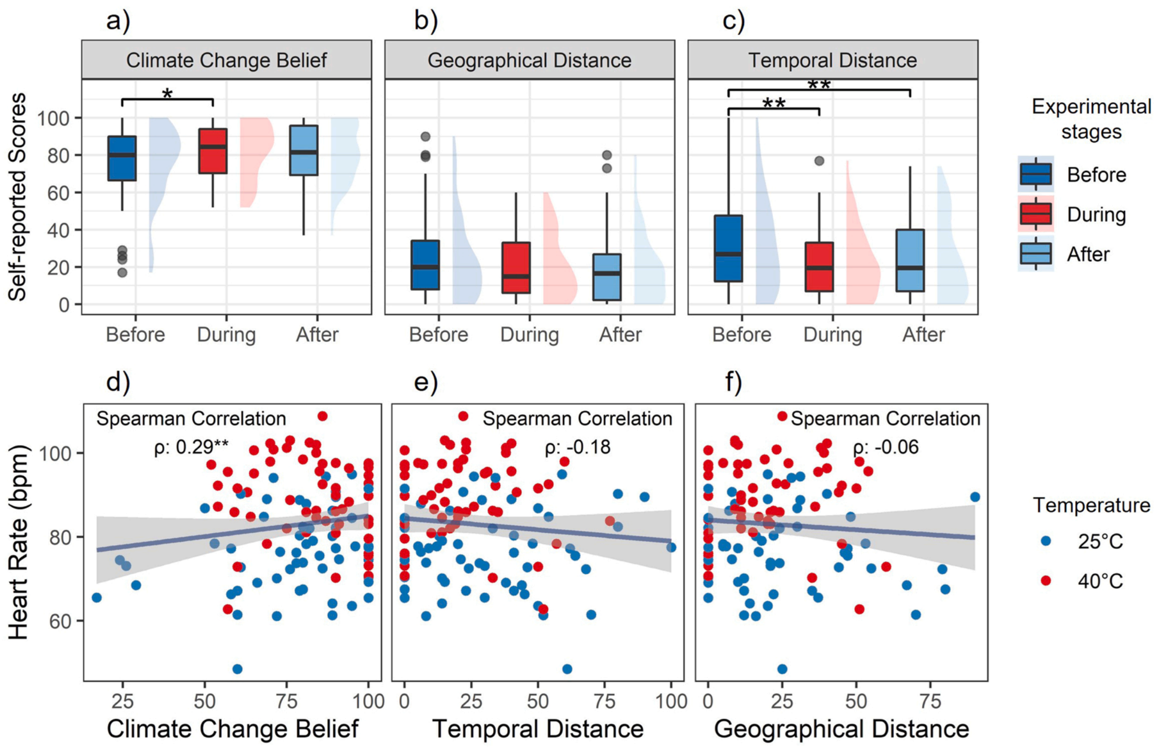

Fig. 4. Climate change perceptions and their correlations with heart rate. Plots a) b) and c) depict climate change belief and psychological distance (geographical and temporal dimensions) before, during, and after the simulated heatwave. Stars denote the Wilcoxon signed-rank test significance. Plots d), e), and f) present the correlation between climate change perceptions and heart rate. Spearman's correlation coefficient ρ and its significance are labeled. (** $p < 0.01$, * $p < 0.05$).

tolerance of local residents. It should be noted that our samples are young and healthy adults without covering different age groups. For seniors especially, subjects' thermal responses may show different patterns.

3.2. The effect of heat exposure on climate change perceptions

We found heat exposure strengthened individuals' climate change belief and reduced psychological distance (Fig. 4abc). Before the heat exposure (25 °C, at Room A), the median of climate change belief, geographical and temporal psychological distance was 80, 20, and 28, respectively. Wilcoxon signed-rank test showed that when exposed to the heat (40 °C, at Room B), the median of climate change belief was elevated to 85 ($p = 0.011$), and medians of geographical and temporal distance were reduced to 15 ($p = 0.279$) and 20 ($p = 0.001$), respectively. It indicated people were more convinced about the existence of climate change and more concerned during the heat exposure. Also, heat exposure did not significantly modify answers to other control questions (Table S9). Those results replicated the "local warming" effect and demonstrate that heat exposure shifts climate change perceptions.

We also calculated the correlation between physiological signals and climate change perceptions. The results showed that heat-induced physiological change was not a very strong predictor of climate change perception. Heart rate was positively correlated with climate change belief, but the effect was small ($\rho = 0.29$, $p = 0.002$) (Fig. 4d). Two psychological distance measures on temporal and spatial dimensions had weak and insignificant correlations with heart rate changes (Fig. 4ef). Similar weak correlations were found between other physiological signals and climate change perceptions (Table S8).

By collecting longitudinal data at the individual level, we proved the causal effect of extreme heat exposure on climate change perceptions. To our knowledge, this is the first study to replicate the 'local warming' effect based on lab experiment. The potential mechanism of the "local warming" effect is worth discussion. The "visceral fit" theory proposed by Risen and Critcher (2011) suggests that when experiencing a certain visceral state, people would judge future states of the world that fit with that experience to be more likely. Accordingly, the physical responses to a warming environment made individuals believe that global warming is more likely to be a reality. However, we found physiological signals like HR only had weak correlations with climate change perceptions. Therefore, our study did not fully support the claim of "visceral fit". More evidence from both panel studies and lab-controlled experiments are needed to validate other relevant theories, such as attribute substitution and mental models (see Supplementary Texts), and reveal the complex psychological mechanism.

Our experimental evidence of the "local warming" effect highlights the chance to promote climate change awareness and encourage individual actions when abnormal heat events occur. Due to strong psychological links between physical experience and climate change concepts, heat events create "windows of opportunity" for local governments to proceed mitigation and adaptation policy agendas. For example, local public agencies or educators should capture the periods with high media attention in the wake of heatwave events and attribute extreme weather to one of the disastrous consequences of climate change. Popular outlets can deliver concrete scientific messages to help the general public realize personal relevance on climate change issues and engage the public in longer-term behavioral changes. Despite these new findings, it is worth noting that in our study, participants were well-educated college students and already had strong climate change beliefs and short psychological distances before the heat exposure. Future works should continue to investigate how the "local warming" effect applies to the lay public.

3.3. Follow-up surveys after the experiment

After the experiment, we found people had a short-term memory of the heat exposure and presented forgetting trends during the follow-up surveys. When participants were asked to recall their thermal perceptions of 40 °C exposure, they recalled lower temperature sensations, higher temperature comfort, and higher temperature acceptability compared to what they reported during the exposure experiment (Fig. 5abc). In contrast, the climate change perceptions did not change significantly (Fig. 5def).

Multilevel modeling (MLM) further revealed factors driving the temporal variations in thermal memory and climate change perception (Table 1). Time point of the follow-up surveys significantly affected recalled thermal sensation, but not temperature comfort and temperature acceptability. The longer time the experiment had passed, the cooler participants felt about the 40 °C experience in their memories ($\beta = -1.37$, SE = 0.53, $p = 0.009$). There was also a main effect of geographical background ($\beta = 4.92$, SE = 2.49, $p = 0.048$). Participants from the South recalled the heat exposure as a hotter experience than those from the North.

In terms of climate change perception, both temporal distance ($\beta = -2.67$, SE = 1.01, $p = 0.008$) and geographical distance ($\beta = -1.13$, SE = 0.47, $p = 0.017$) reduced significantly as time went by. Gender, geographical background, and daily temperature did not predict the changes in psychological distance. On the contrary, climate change belief did not change significantly with time but was influenced by the maximum temperature on the survey day and the respondent's geographical background. Specifically, higher maximum daily temperature ($\beta = 0.446$, SE = 0.33, $p = 0.038$) led to stronger climate change belief. Participants from the South were more certain about the existence of climate change over time ($\beta = 9.27$, SE = 4.56, $p = 0.042$). The strong influence of maximum temperature demonstrated that in the absence of extreme experimental heat exposure, daily weather variations still affected individual climate change perceptions (i.e., the "local warming" effect). These results also agreed with the "attribution substitution" theory, suggesting that individuals tend to use less relevant but more salient and available information such as current temperature to make judgments about climate change (Zaval et al., 2014).

The follow-up survey results also have implications for extreme heat warnings and climate change communications. Short memory of heat experience suggests that extreme heat risks may be widely underestimated by the general public. Even in regions in which heat wave events occur frequently, people seem not to learn from their past experience. Therefore, effective heat warning systems should deliver targeted messages to raise public attention and motivate adaptation actions. Regarding the "local warming" effect in the absence of extreme weather conditions, national polling results should be interpreted with caution due to the potential bias caused by daily temperature variations (Howe et al., 2019; Zaval et al., 2014). When surveying climate change opinion, researchers should pay attention to how the survey questions are framed. For example, reminding respondents to think about temperature patterns over the last year can help eliminate the "local warming" effect (Druckman, 2015).

4. Conclusions

In this study, we designed a lab-based experiment to inform two major gaps in making adaptaion policies for extreme heat event. To set

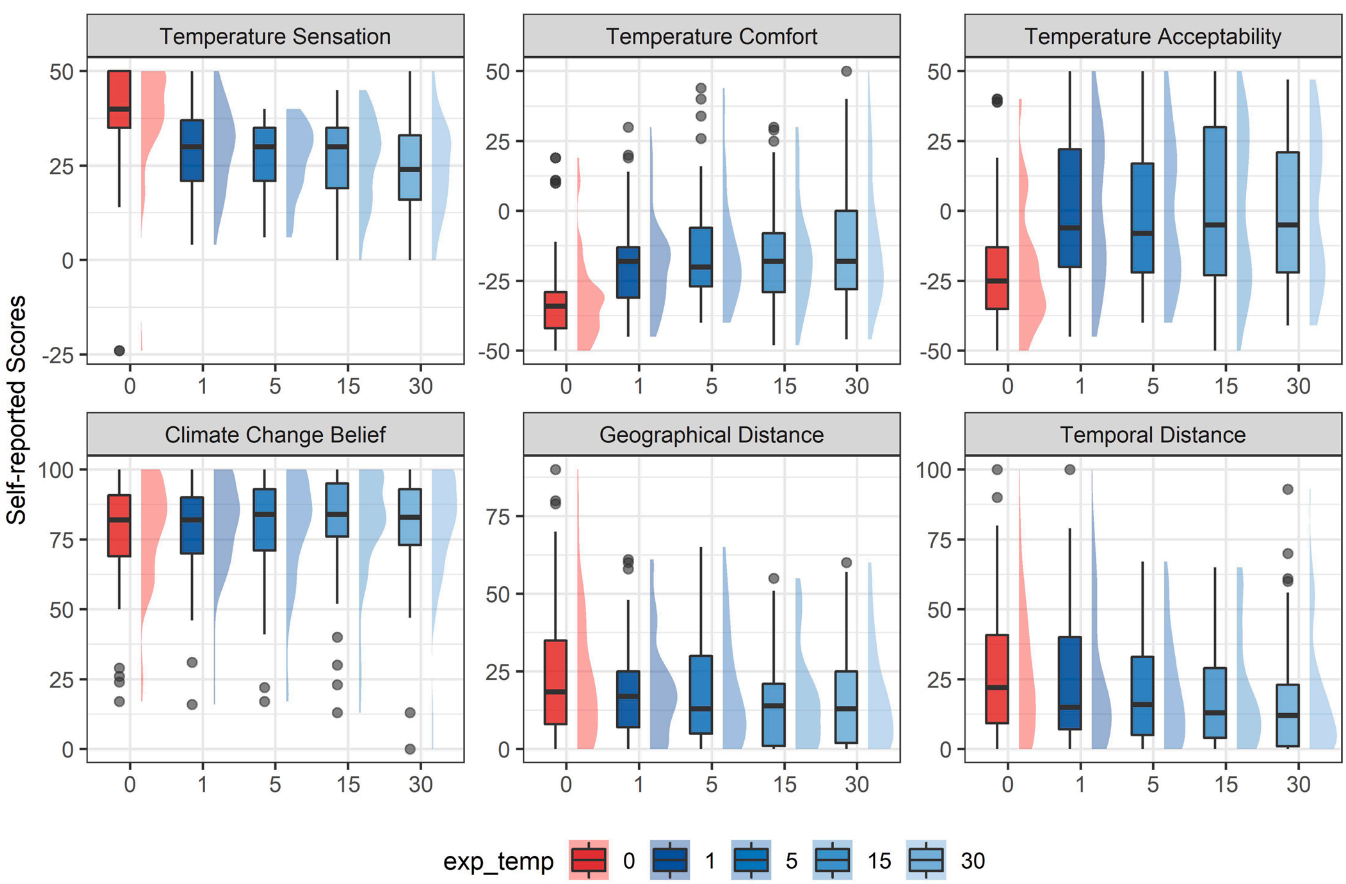

Fig. 5. Thermal perceptions of recalled heat exposure and climate change perceptions in follow-up surveys. Plots a), b), and c) present survey results of thermal sensations, temperature comfort, and temperature acceptability of recalled heat exposure. Plots d), e), and f) present measures of climate change perceptions. Timepoint 0 indicates surveys during the heat exposure (40 °C). Timepoints 1, 5, 15, and 30 indicate surveys at the 1st, 5th, 15th, 30th days after the experiment.

Table 1
Multilevel modeling estimates of follow-up surveys after the heat exposure.

	Temperature Sensation			Temperature Comfort			Temperature Acceptability			Temporal Distance			Geographical Distance			Climate Change Belief		
Predictors	*β*	*SE*	*p*	*β*	*SE*	*p*	*β*	*SE*	*p*	*β*	*SE*	*p*	*β*	*SE*	*p*	*β*	*SE*	*p*
(Intercept)	22.90	3.87	**< 0.001**	-3.44	7.21	0.633	3.73	8.29	0.653	30.97	7.65	**< 0.001**	21.85	5.01	**< 0.001**	68.39	6.31	**< 0.001**
Time	-1.37	0.53	**0.009**	0.98	0.99	0.322	0.57	0.93	0.538	-2.67	1.01	**0.008**	-1.13	0.47	**0.017**	0.52	0.79	0.517
Gender	1.62	2.52	0.521	-3.21	4.66	0.490	-11.87	6.85	0.083	2.51	5.27	0.634	-1.64	4.60	0.722	-7.26	4.62	0.116
Max_Temp	0.12	0.22	0.583	-0.73	0.41	0.074	0.37	0.39	0.340	-0.34	0.42	0.419	-0.15	0.20	0.446	0.69	0.33	**0.038**
Min_Temp	0.02	0.25	0.922	0.44	0.46	0.340	-0.19	0.43	0.657	0.13	0.47	0.787	0.13	0.22	0.554	-0.67	0.37	0.070
Geo_Background	4.92	2.49	**0.048**	-2.78	4.60	0.546	-8.97	6.77	0.185	-2.67	5.20	0.608	-0.38	4.54	0.933	9.27	4.56	**0.042**
Random Effects																		
σ^2	44.92			157.92			138.17			164.58			35.73			102.14		
τ_{00}	66.71 $_{ID}$			226.20 $_{ID}$			540.23 $_{ID}$			298.26 $_{ID}$			249.66 $_{ID}$			235.35 $_{ID}$		
ICC	0.60			0.59			0.80			0.64			0.87			0.70		
N	57 $_{ID}$			57 $_{ID}$			57 $_{ID}$			57 $_{ID}$			57 $_{ID}$			57 $_{ID}$		
Observations	228			228			228			228			228			228		
Marginal R^2 / Conditional R^2	0.081 / 0.630			0.031 / 0.602			0.057 / 0.808			0.021 / 0.652			0.007 / 0.876			0.105 / 0.729		

Reference category for gender (1 = male); Reference category for geographical background (1 = south)
SE: standard error; $\boldsymbol{\sigma^2}$: mean squared error; $\boldsymbol{\tau_{00}}$: random intercept variance; **ICC:** intraclass-correlation coefficient.

proper thresholds of heat warning systems, empirical knowledge of human experimentation in heat chambers can provide deeper insights about how heat exposure affects physiology and subjective thermal perceptions. In our case city, we found physiological responses were highly correlated with subjective thermal votes. Both indicators show sharp rises from 30° to 35°C. The issuance of a local heat warning may need to consider some sustained periods of hot weather between 30 and 35 °C. Via a 30-days follow-up survey after the experiment, we observed a forgetting trend of recalled thermal response. It suggests that people do not learn from their past experience and effective heat warning systems are necessary for delivering targeted and timely messages to raise public attention and motivate adaptation actions.

We also testified the "local warming" effect. By comparing climate change perceptions before, during and after experiment, we found heat exposure significantly increased climate change belief and reduced temporal psychological distance. In the follow-up surveys, daily temperature variations predicted climate change belief, indicating the "local warming" effect still existed in the absence of extreme temperature. These findings underscore a "window of opportunity" for communicating climate change risks and proceeding climate agenda during extreme weather events. Also, opinion polls should also take the "local warming" effect into account to reduce potential bias caused by daily temperature variations.

CRediT authorship contribution statement

Jianxun Yang: Conceptualization; Investigation; Formal analysis; Writing – original draft. **Qi Gao:** Investigation. **Miaomiao Liu:** Conceptualization; Investigation; Writing – review & editing. **Qingqing Wang:** Conceptualization; Funding acquisition. **Zhen Ding:** Funding acquisition; Supervision. **Mao Liu:** Investigation; Formal analysis. **Jun Bi:** Funding acquisition; Project administration.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.06.002.

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