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ANALYSIS

Rising temperatures and physical pain: Evidence from over 2 million U. S. residents

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A R T I C L E I N F O

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A B S T R A C T

Physical pain is on the rise worldwide, yet little is known about its relationship with rising temperatures. Using daily survey data on more than 2 million U.S. residents from 26,987 zip codes between 2008 and 2017, we examine whether hotter days are associated with greater reports of pain. Our outcome captures whether respondents experienced physical pain for a substantial part of the day, reflecting the prevalence of sustained daily pain rather than fleeting discomfort. We find that the likelihood of such pain increases steadily with temperature up to around 16–18 °C and remains elevated, though with smaller further increases, on hotter days. On days with temperatures of 32 °C or higher, the probability of reporting pain is about 0.45 percentage points higher—an increase of roughly 1.9 % relative to the average prevalence. Analyses of stress, enjoyment, and activity limitation suggest that physiological pathways play an important role in this association, complementing possible behavioural responses. Using climate projection data (CMIP5, SSP2–4.5), we estimate that temperature-driven increases in pain prevalence between 2008 and 2017 imposed annual economic costs of approximately $2 billion, with projected costs rising to $9.4 billion by 2050 if no adaptation measures are taken. These findings suggest that temperature deviations from moderate ranges exacerbate physical suffering, with the heat effects likely understated in our data, and underscore the need for policies that mitigate both climatic and health impacts.

1. Introduction

Physical pain is a ubiquitous human experience that can be triggered by physical injuries or emotional circumstances (Raja et al., 2020). Over the past decade, reports of pain have been on the rise globally (Macchia, 2022), exerting substantial consequences for the economy, healthcare, and quality of life (Lin et al., 2011; Gaskin and Richard, 2012; McNamee and Mendolia, 2014). Despite extensive research into the socio-economic and psychosocial determinants of pain—including economic recessions (Macchia and Oswald, 2021), job strain (Amiri and Behnezhad, 2020), income inequality (Tang et al., 2023), financial insecurity (Chou et al., 2016), and adverse childhood experiences such as low socioeconomic status (Jay et al., 2019) and maternal depression (Goosby, 2013)— little attention has been paid to environmental determinants. In particular, the potential role of rising temperatures as a contributor to the growing prevalence of pain in contemporary society remains underexplored.

Extensive research has explored the consequences of rising global temperatures on human health (Campbell-Lendrum et al., 2023; Ebi et al., 2021a, 2021b; Patz et al., 2014; Woodward et al., 2014). The findings are unequivocal: increased exposure to extreme weather events and rising temperatures poses significant health risks, including infectious diseases (Lafferty, 2009), heart and respiratory diseases (Ebi et al., 2021a, 2021b), malnutrition due to global food shortages (Fanzo et al., 2018), disrupted sleep patterns (Bigler and Janzen, 2024), and injuries resulting from natural disasters linked to global warming (van Aalst, 2006). In addition to physical health threats, studies document substantial mental health risks associated with hotter conditions (Kjellstrom and Crowe, 2011; Obradovich et al., 2018; Ogunbode et al., 2023). Such impacts may operate both directly and indirectly, through pathways including disruptions to economic activity (Fankhauser and Tol, 2005), increased social conflict (Hendrix and Salehyan, 2012), ecological grief in response to climate-related losses (Cunsolo and Ellis, 2018), and psychological trauma following climate-induced natural disasters (Kessler et al., 2008). Importantly, many of these same pathways—such as sleep disruption, heightened stress, and physiological strain—are also

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known correlates of physical pain, making the link between rising temperatures and pain a plausible but underexplored avenue of research.

There are two possible pathways through which heat can influence pain. A behavioural explanation suggests that hotter days may lead to increased outdoor activity and exertion, thereby raising the risk of injury and discomfort (Obradovich and Fowler, 2017). A non-behavioural explanation instead emphasises that heat can directly worsen pain, either through physiological stress—such as disrupted sleep, inflammation, or thermal strain—or via psychological mechanisms, like heightened stress and negative affect that intensify pain perception (Macfarlane et al., 2010; Obradovich et al., 2018). These contrasting views underscore the need for systematic evidence on how temperature relates to self-reported pain at the population level.

While the detrimental effects of rising temperatures on physical and mental health are well-documented, evidence on their role in physical pain remains limited and often inconsistent (Horvath et al., 2023; Macfarlane et al., 2010; Redelmeier and Tversky, 1996; Telfer and Obradovich, 2017; Yimer et al., 2022). Large-scale studies are scarce. A review of more than 4700 research papers found most relied on small samples, crude exposure measures, and inconsistent statistical methods (Beukenhorst et al., 2020). Even larger contributions, such as Telfer and Obradovich (2017), typically use aggregated data like city-level climate data or Google Trends searches for pain-related symptoms, which cannot capture nuanced, individual-level experiences. This lack of systematic evidence on how rising temperatures influence self-reported pain presents a significant challenge for both health researchers and policymakers. The stakes are high: pain is a major contributor to the opioid epidemic in the United States (Case and Deaton, 2015) and the rise in "deaths of despair" linked to suicides, overdoses, and alcohol-related fatalities (McGreal, 2018). Addressing this deficiency is therefore essential for developing targeted interventions to mitigate these intersecting public health crises of climate change, chronic pain, and substance misuse.

This study addresses the gap by examining the relationship between temperatures and self-reported physical pain among more than two million individuals across the United States between 2008 and 2017, using data from the Gallup-Healthways Well-Being Index (GHWI). The GHWI is a large, nationally representative survey that records daily measures of pain alongside a wide range of socio-demographic and contextual characteristics. Its richness allows us to overcome the limitations of prior work in three important ways. First, its size and coverage ensure externally valid estimates from a representative sample rather than narrow patient groups or aggregated search data. Second, its daily measures of both pain and local weather conditions enable us to analyse contemporaneous responses to heat, minimising concerns about recall bias and misclassified exposures. Third, the data permit investigation of heterogeneous effects across demographic groups and, crucially, between individuals who spend most of their time indoors versus outdoors, thereby allowing us to probe competing behavioural and non-behavioural explanations. **By exploiting granular variation in weather across 26,987 U.S. zip-codes and including rich fixed effects, our empirical design further reduces concerns about confounding from unobserved geographic or temporal factors.** Together, these features make the GHWI uniquely suited to provide systematic evidence on how rising temperatures affect the lived experience of physical pain.

Our analysis reveals that on days when temperatures reach 32 °C or higher, individuals are about 0.45 percentage points more likely to report physical pain, corresponding to roughly a 1.9 % increase relative to the baseline prevalence. The effects are not evenly distributed. They are considerably weaker among older respondents, consistent with greater avoidance of heat exposure in this group, but markedly stronger among lower-income households, suggesting that limited access to defensive investments such as air conditioning leaves poorer individuals more vulnerable (Davis et al., 2021). We also find that the association between heat and pain is present even among respondents whose occupation requires them to spend most of their time indoors, indicating that behavioural pathways alone cannot account for the observed pattern. At the same time, the relationship is not unbounded: beyond very high temperatures, the marginal effect of additional heat appears to plateau, suggesting a ceiling effect in self-reported pain of this duration and salience. Complementary analyses of affective well-being outcomes and activity limitation provide some indication that non-behavioural mechanisms—such as physiological strain or heightened negative affect—may play a role in linking temperature to pain.

2. Empirical strategy

2.1. Data

We draw on data from the Gallup-Healthways Well-Being Index (GHWI), a nationally representative daily survey of adults in the United States conducted between 2008 and 2017. The GHWI provides one of the richest resources available for studying well-being at scale, covering more than two million respondents across all fifty states and the District of Columbia. Participants are recruited through random-digit dialling, and sampling weights allow inference to the broader U.S. adult population.

Our primary outcome of interest is based on the survey item: "*Did you experience feelings of physical pain a lot yesterday?*" Responses are coded as binary indicators. While the question does not measure pain intensity, it captures whether pain was sufficiently salient and persistent to be reported as lasting much of the day. We therefore interpret it as a measure of prevalent pain rather than feeling discomfort.

To measure exposure to heat, we match each respondent to the daily maximum temperature in their residential zip-code, using high-resolution gridded weather data that provide fine-grained spatial coverage across 26,987 zip-codes (Di Luzio et al., 2008).[1] This allows us to identify, contemporaneous exposure with substantially greater precision than prior studies that rely on aggregated city-level averages. For interpretability, we group temperature into bins (e.g., <10 °C, 10–15 °C, …, ≥32 °C), following established approaches in the temperature-health literature.

In addition to pain, the GHWI records daily reports of affective states such as happiness, enjoyment, stress, sadness, worry, and laughter. These outcomes enable us to investigate whether the relationship between rising temperatures and pain operates partly through psychological pathways. The survey also asks whether health limited respondents' daily activities, which we use as an indicator of activity limitation. Together, these outcomes provide complementary evidence on potential mechanisms.

Moreover, the breadth of the GHWI enables us to examine heterogeneity across socio-demographic groups. We focus on age, gender, and income, given their centrality in both the health and climate-adaptation literatures. Crucially, the survey includes information on respondents' exercise and occupations, allowing us to classify whether they spend most of their time indoors or outdoors at work. This variable allows us to distinguish between behavioural explanations, which emphasise exposure and exertion, and non-behavioural mechanisms, which imply that heat can exacerbate pain even when individuals remain largely indoors.

Finally, we augmented daily cloud cover, relative humidity, and windspeed from the National Centres for Environmental Prediction Reanalysis II project at 2.5 degrees latitude and longitude resolution (Kanamitsu et al., 2002) before aggregating the data to county-year levels. These variables are included as controls because they capture additional weather conditions—such as humidity, wind, and

[1] Specifically, we aggregate daily temperature and precipitation at the grid-level to the zip-code level to compute average daily maximum temperature and rainfall. Subsequently, we define the daily temperature and rainfall bins for each zip-code based on these averaged measures.

sunlight—that may independently influence pain or mood, helping to isolate the effect of temperature. Table S1 in the Supplementary Materials provides detailed definitions of all variables used in the analysis, while Table S2 reports the corresponding descriptive statistics.

2.2. Identification strategy

To estimate the daily weather effects on physical pain, we estimate the following regression model:

$$P_{izcsdt} = \sum_b \varphi^b \overline{ATMAX}_{zb}^{\{d-1,d\}} + \sum_k \delta^k \overline{APRECP}_{zk}^{\{d-1,d\}} + \sum_j \mu^j D_{cj}^{\{t-1\}} + X'_i\beta + Z'_{zd}\eta + \alpha_z + \pi_d + (\theta_s \times \kappa_t) + \varepsilon_{izcsdt}. \quad (1)$$

P_{izcsdt} represents a binary indicator of self-reported physical pain (1 = yes, 0 = no, multiplied by 100 for percentage interpretation) for individual i residing in zip-code z at county c and state s completing the survey on date d in year t. The main explanatory variables are the average daily maximum temperature, $\overline{ATMAX}_z^{\{d-1,d\}}$, and daily precipitation, $\overline{APRECP}_z^{\{d-1,d\}}$, recorded on the interview day and the preceding day in zip-code z. To capture the non-linear effects of warming on physical pain, we categorise average maximum daily temperature into 2 °C bins and precipitation into 5 mm bins, following Obradovich et al. (2018). Days between 16 and 18 °C and with no rainfall serve as baselines.

We further include controls for contemporaneous meteorological conditions—diurnal temperature range, cloud cover, relative humidity (and its square), and wind speed (and its square)—to address the possibility that other weather factors confound the relationship between temperature and pain. The vector X_i contains individual characteristics plausibly related to pain: age, gender, race, household income, marital status, number of children, body mass index (and its square), caring responsibilities, and occupation type.

To address unobserved spatial heterogeneity, we include zip-code fixed effects (α_z) and state-by-year fixed effects ($\theta_s \times \kappa_t$), and add survey date fixed effects (π_d) to absorb nationwide shocks and seasonality. This specification exploits within-zip variation over time, comparing individuals exposed to different daily temperatures in the same location. Standard errors are clustered at the zip-code level, the most granular geography at which treatment varies; robustness checks confirm results under county- and state-level clustering.

Beyond estimating average effects, we also examine potential mechanisms discussed in the literature. Behavioural pathways are explored by interacting heat exposure with indicators for outdoor versus indoor occupations and by analysing reported exercise frequency. Non-behavioural pathways are investigated using GHWI measures of stress, enjoyment, and activity limitation. These analyses provide suggestive evidence on whether heat increases pain primarily through exposure-related behaviour or through direct physiological and psychological strain.

Identification relies on the assumption that, conditional on rich controls and fixed effects, daily temperature fluctuations are as good as random with respect to unobserved determinants of pain. To the extent that individuals who are most adversely affected by extreme heat are less likely to respond to the survey—for example, because they are unwell, fatigued, or otherwise unable to participate—our estimates will understate the true effect of temperature on pain. In other words, any systematic non-response among those most vulnerable would bias our results downward, making them conservative. A further reason why our estimates may represent a lower bound is the nature of the outcome variable. The GHWI item asks whether respondents experienced physical pain "*during a lot of the day yesterday*," which captures only more salient and persistent cases of pain. It does not account for less severe or shorter-duration pain episodes that may also be triggered or worsened by heat. Taken together, these considerations suggest that our findings likely underestimate the full welfare impact of rising temperatures on pain.[2]

3. Results

3.1. Baseline results

Fig. 1 presents descriptive evidence on the link between temperature and pain prevalence across U.S. counties from 2008 to 2017. Panels A and B display the spatial distribution of daily maximum temperature and the share of respondents reporting pain, while Panel C illustrates their positive correlation across counties. Panel D then tracks annual changes relative to 2008, showing that pain rose by roughly 4 percentage points over the decade, alongside an increase of about 1 °C in maximum temperature. The co-movement suggests that warming may have partially contributed to the upward trend in pain. These patterns motivate the regression analysis that follows, which quantifies the spatial and time-series relationship more systematically.

Estimated effects from eq. (1) are illustrated in Fig. 2. We find that, across different specifications, pain levels are lowest at cold temperatures, increase as temperatures go above a comfortable level, and stay high on hotter days. Compared to the baseline category of 16–18 °C, days with a maximum temperature of 32 °C or above are associated with a 0.45 percentage point ($p < 0.05$) higher likelihood of reporting pain, equivalent to a 1.9 % increase relative to the baseline prevalence of 24 %.

While the estimated 1.9 % increase may appear modest, it is comparable in magnitude to other well-documented socio-economic determinants of pain, such as job strain or financial insecurity (Amiri and Behnezhad, 2020; Chou et al., 2016). Moreover, unlike much of the prior weather–pain literature, which is often based on small samples or indirect indicators (Redelmeier and Tversky, 1996; Telfer and Obradovich, 2017), our estimate derives from more than two million individuals, making it one of the most precise and policy-relevant effect sizes to date.

Fig. 2 further illustrates that the relationship between temperature and pain is roughly linear from cold temperatures up to about 22–24 °C. Beyond this point, the curve flattens, indicating that the probability of reporting pain does not increase further at higher temperatures. This plateau suggests a possible ceiling effect in reported pain, likely reflecting the binary nature of the survey item rather than a genuine levelling off in underlying pain intensity.

Next, we compile the estimated effects across the temperature bins to calculate the nationwide predicted change in pain prevalence resulting from temperature changes. The specification takes the following form:

$$\boldsymbol{P}_t^{Nat} = \sum_{i=1}^{N_t} \omega_z \bullet \hat{f}\left(\overline{ATMAX}_{zt}^{\{d-1,d\}}\right) - \hat{f}\left(\overline{ATMAX}_{z(2000)}^{\{d-1,d\}}\right) \quad (2)$$

[2] We further estimate longer run effects of temperature and precipitation on physical pain using a first-differenced specification. Since estimated effects are quantitatively similar to the empirical specification in equation (1), due to space constraints, we relegate in-depth discussion of these findings in Table S5 in the SM.

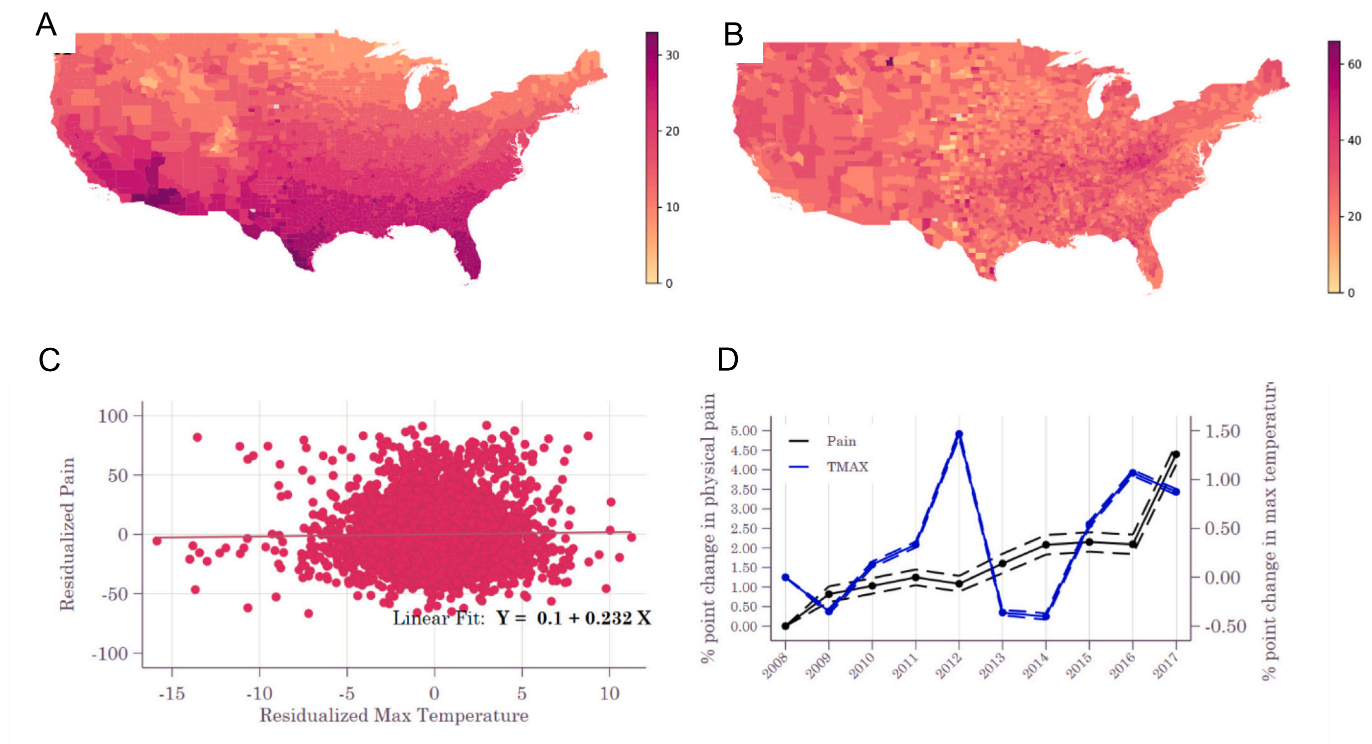

Fig. 1. Spatial distribution of temperature and physical pain across counties in the US from 2008 to 2017. Panel (A) displays the daily maximum temperature. Panel (B) presents the percentage of respondents experiencing pain. Panel (C) shows the scatter plot and linear fit between residualised maximum temperature and residualised pain measures across counties over time. We construct residualised temperature and pain measures by regressing these variables against a comprehensive set of controls, as indicated in eq. 1, before predicting the residuals. Panel (D) illustrates the change in the percentage points of physical pain and maximum temperature over time. These estimates are derived from the coefficients of year binary variables from an empirical model regressing pain probabilities against zip-code fixed effects. Tails denote 95 % confidence intervals constructed from standard errors clustered at the zip-code level.

where $\boldsymbol{P}_t^{Nat}$ is the nationwide population-weighted average change in pain prevalence, weighted by population in zip-code z (based on the American Community Survey in 2020), at year t due to deviation in temperature from the 2000 baseline. This is computed based on the difference in the predicted effect on pain based on the temperature experienced by the respondent ($\widehat{f}\left(\overline{ATMAX}_{zt}^{\{d-1,d\}}\right)$) and the predicted effect on pain based on the temperature on the same day and month in the year 2000 ($\widehat{f}\left(\overline{ATMAX}_{z(2000)}^{\{d-1,d\}}\right)$), holding all other factors constant. Here, we assume that if there were no climate change, weather conditions would follow those of the year 2000. The rationale for weighting is to ensure that our estimates are more representative of the US by accurately accounting for the spatial distribution of population. The nationwide average predicted increase in pain prevalence due to temperature deviation between 2008 and 2017 is approximately 0.085 %, corresponding to roughly 270,000[3] additional individuals suffering from pain each year.[4] Based on the economic cost of pain of $7500 per person per year (in 2020 dollars), as reported by Gaskin and Richard (2012), temperature-driven pain prevalence could impose a nationwide annual cost of up to $2 billion.

We further augment projected climate data from Coupled Model Intercomparison Project Phase 5 (CMIP5) to understand how future climate changes may impact pain levels.[5] Based on the middle-of-the-road socioeconomic pathway (SSP) (SSP2–4.5), and if individuals do not adapt their behaviours to climate change to reduce heat effects on pain, our estimates suggest that by 2050, the nationwide predicted increase in pain due to temperature changes is 0.36 %. Given that the population is projected to be 360 million by 2050 by the US Census Bureau (US Census Bureau, 2023), we expect another 1.31 million individuals to be suffering from physical pain, which will impose a staggering future economic cost of $9.4 billion. Taking this estimate at face value, these associations would correspond to substantial immediate and future economic costs, highlighting the urgent need for policies to mitigate these health impacts.

3.2. Robustness tests

3.2.1. Different temperature bin definitions and clustering choices

We conducted a series of robustness tests to verify that the documented relationship between heat and physical pain is not spurious.

First, we examined whether our findings were sensitive to the definition of temperature bins. *Re*-estimating the model with narrower (1 °C) and broader (4–5 °C) bins yields results consistent with the baseline specification (Figs. 3a–3c). In all cases, hotter days are associated with a higher probability of self-reported pain, underscoring that the relationship is not an artefact of binning methodology.

Second, we performed a falsification test by replacing contemporaneous temperatures with temperatures measured 7, 14, and 30 days

[3] 0.00085 × 315 million U.S. residents in the year 2000 = approximately 270,000.

[4] Due to space limitations, we present average annual estimates by computing the average of $\boldsymbol{P}_t^{Nat}$ between 2008 and 2017.

[5] Similar to before, to compute future changes in pain prevalence in 2050, we substitute future climatic conditions in 2050 to predict changes in pain prevalence before taking the difference from predicted changes in pain prevalence due to climatic conditions in 2000 as denoted in equation (2), before following the same procedure to compute nationwide estimates in pain prevalence.

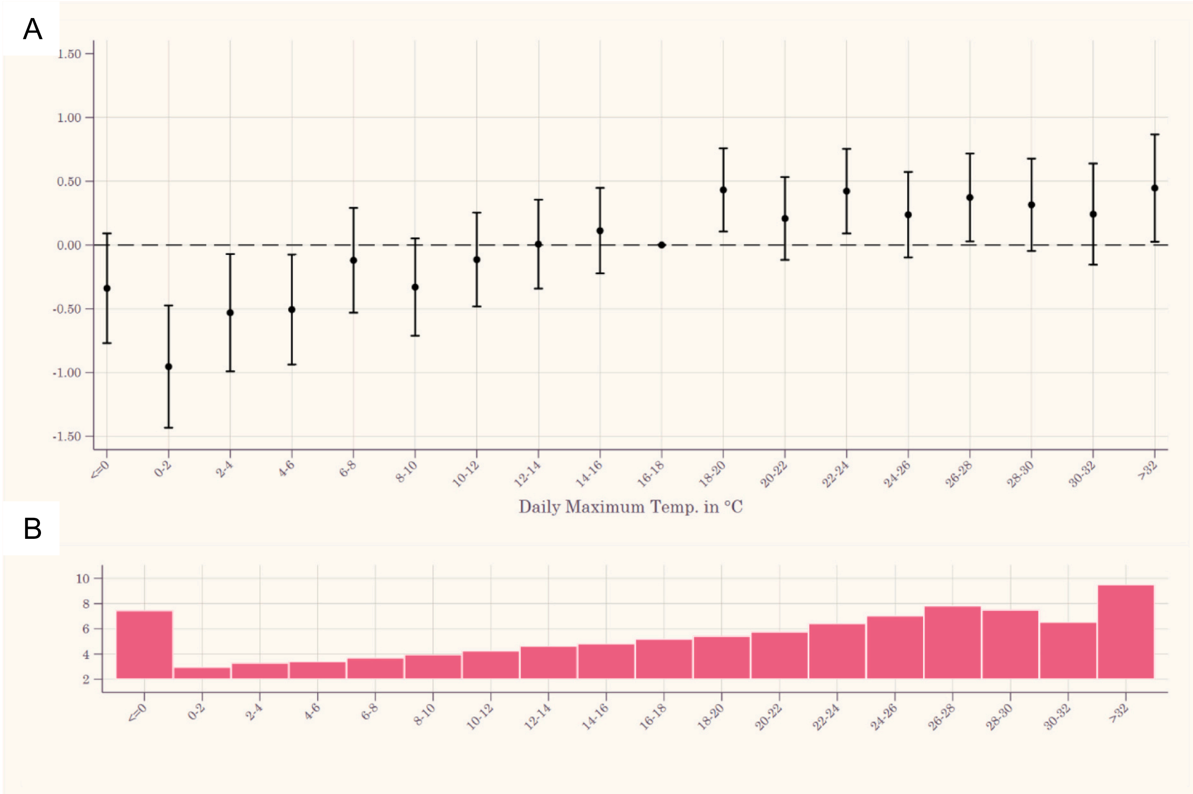

Fig. 2. The association of heat (in 2-degree bins) and precipitation (in 5 mm bins) with physical pain. Panel (A) reports the estimated relationship between heat and the probability of physical pain, which is a binary variable multiplied by 100. The baseline group for comparison is 16–18 degrees Celsius. Panel (B) reports the corresponding histogram that denotes the percentage of observations for each group. 95 % confidence intervals, which are denoted by the tails, are constructed from standard errors clustered at the zip-code level. $N = 2{,}168{,}980$, zip-code = 26,987. **Estimates are reported in column 6 of Table S3.**

after the interview. As expected, the estimated effects vanish across all three horizons (Figs. 3d–3f), consistent with the assumption that future weather cannot influence past reports of pain.

Third, we assessed sensitivity to alternative error structures and control variables. Our main results cluster standard errors at the zip-code level, where weather exposure varies most finely, but estimates remain robust when clustering at county and state levels. Likewise, excluding natural disaster controls, or alternatively including them alongside other covariates, does not meaningfully alter the results (Column 5 Table S3). Finally, while religiosity is excluded from the baseline model to avoid potential endogeneity with climate shocks, including it as a control leaves the estimated heat–pain relationship unchanged (Column 6 Table S3).

3.2.2. Heterogeneous effects across subgroups

We next investigate whether the heat–pain relationship differs across demographic and socioeconomic groups. Fig. 4 plots the estimates stratified by gender, age, and household income.

For gender, we find slightly larger point estimates for men (0.56 percentage points) than for women (0.39 percentage points) at daily maximum temperatures of 32 °C or above, but the difference is not statistically significant. This suggests that, in contrast to some studies that emphasise gendered differences in pain sensitivity (e.g., Bartley and Fillingim, 2013), the burden of heat-related pain appears broadly shared across men and women in the general population.

For age, the strongest effects are observed among middle-aged adults (25–54 years), where hot days are associated with a 0.58 percentage point increase in the probability of reporting pain. In contrast, effects are negligible for younger ($\leq$25 years) and smaller for older ($\geq$55 years) respondents. This pattern is consistent with behavioural avoidance among the elderly: despite their well-documented physiological vulnerability to heat (Basu, 2009), older individuals may be more likely to remain indoors or adjust activity patterns, thereby mitigating exposure (Rabassa et al., 2021). The null result for younger adults may reflect both lower baseline pain prevalence and greater physiological resilience, in line with prior work showing that musculoskeletal and chronic pain increase with age (Macfarlane et al., 2010).

For income, we find a sharp socioeconomic gradient. Among lower-income respondents (<$12,000/year), hot days are associated with a 2.19 percentage point increase in the probability of reporting pain, equivalent to a 5.1 % increase relative to their baseline prevalence of 42.9 %. By contrast, the effect is negligible for middle- and higher-income groups. This divergence resonates with findings that poorer households have fewer defensive investments, such as air conditioning, and are more likely to work in physically demanding or heat-exposed environments (Davis, 2015). The results also complement broader evidence that climate change disproportionately burdens disadvantaged populations such that the heat-mortality relationship is stronger for lower-income groups (Hsiang et al., 2017; Carleton et al., 2022).

Taken together, these subgroup results highlight the unequal distribution of heat-related pain. The weaker effects among older adults are consistent with behavioural avoidance, while the stronger effects among poorer households point to resource constraints on adaptation. These patterns suggest that both behavioural and non-behavioural factors may be at work.

3.3. Mechanisms

To investigate these possibilities more directly, we next examine two pathways through which heat may influence pain. A behavioural pathway posits that higher temperatures alter activity patterns—-through exercise, work, or recreation—that increase the risk of pain. A

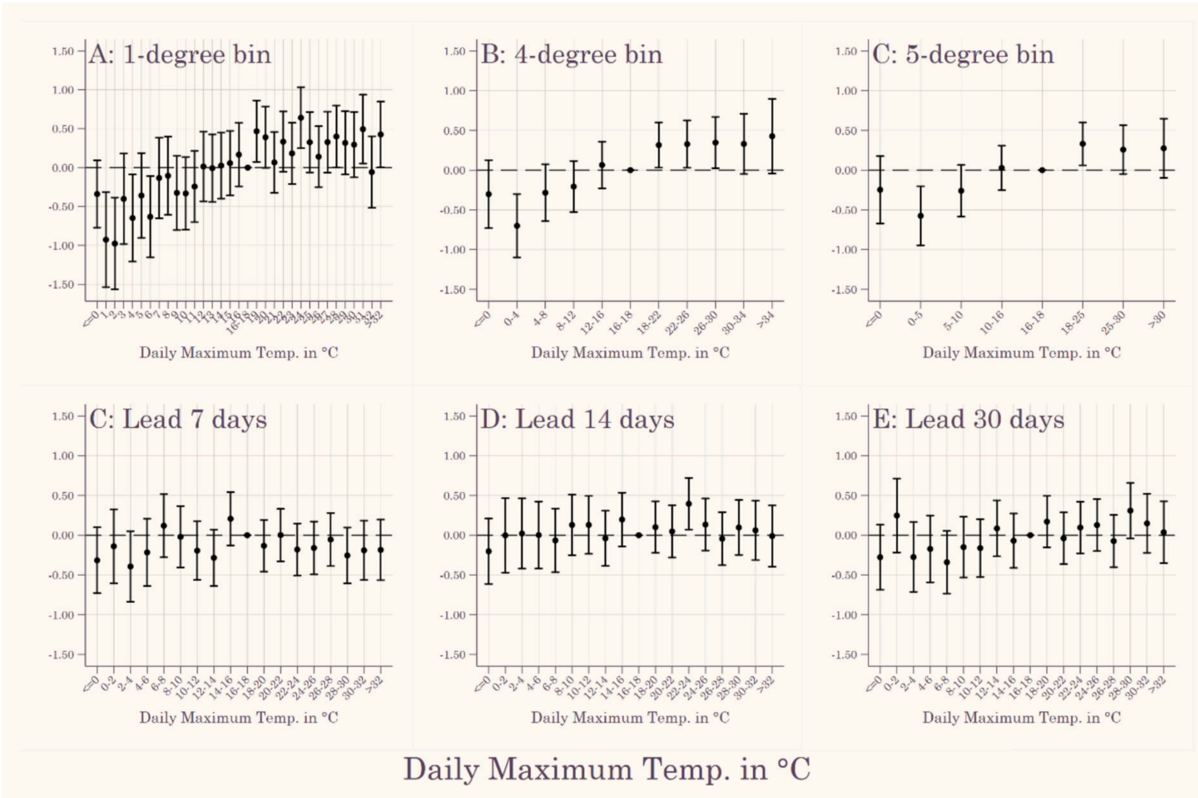

Fig. 3. Robustness tests. Panels (A), (B) and (C) report the association of heat with physical pain in 1-, 4- and 5-degree bins, respectively. Panels (D), (E) and (F) further report estimates from our falsification tests documenting the relationship of temperature 7, 14 and 30 days ahead of the date of the interview with physical pain on day 0, respectively. 95 % confidence intervals, which are denoted by the tails, are constructed from standard errors clustered at the zip-code level. N = 2,168,980, Zip-code = 26,987.

non-behavioural pathway suggests that heat directly heightens stress or psychological strain, thereby intensifying pain perception. To test between these explanations, we analyse whether hot days are associated with differences in exercise, occupational exposure (indoor vs. outdoor work), and activity limitation, and whether they affect reported emotional states such as stress, enjoyment, or sadness.

We begin by testing whether exercise could account for the heat–pain relationship, with results shown in Fig. 5a. Here, the dependent variable is a binary indicator equal to 1 if the respondent exercised for more than 30 min in the past 7 days, and 0 otherwise. Relative to the baseline category of 16–18 °C, the probability of exercising is lower on colder days, but increases steadily as temperatures rise into the mid-20s. The probability of exercise is around 1.3 to 1.5 % higher between 26 and 28 °C and 30–32 °C, before decreasing to 1.1 % beyond 32 °C, denoting slight but imperceptible avoidance behaviours toward extreme heat. Overall, these patterns indicate that hotter days are associated with modest increases in exercise. At first glance, this is consistent with the behavioural pathway hypothesis that heat encourages more physical activity, potentially leading to greater pain prevalence (Telfer and Obradovich, 2017).

However, when we examine the link between exercise and pain directly, the evidence points the other way: respondents who report exercising more frequently are less likely to report pain (see Fig. 5b). This likely reflects selection bias, since individuals already experiencing pain are less able to exercise. Hence, the results suggest that although higher temperatures are associated with modest increases in exercise, the exercise–pain relationship is inconsistent with the behavioural pathway being the primary explanation for the observed heat–pain association.

We next contrast respondents in predominantly indoor occupations—such as professional/managerial, service, and sales/office roles—with those in predominantly outdoor occupations—such as construction, transportation, and farming. If the behavioural-exposure channel were the primary driver, effects should be concentrated among outdoor workers. Instead, Fig. 5c shows the opposite pattern: for indoor workers, the heat–pain gradient is clearly positive relative to the 16–18 °C baseline and remains above zero across the hotter bins, whereas for outdoor workers, as depicted in Fig. 5d, the estimates hover close to zero with wide confidence intervals. This pattern weakens the behavioural-exposure explanation and points toward non-behavioural mechanisms—such as physiological strain or psychological stress that operate even with limited outdoor exposure—as more plausible contributors to the heat–pain relationship.

Three caveats help interpret this contrast. First, outdoor workers may represent a selected, hardier group (a "healthy-worker effect") and may also adopt protective practices such as hydration, scheduled breaks, and shade, which attenuate measured effects. Second, measurement error in the classification of indoor versus outdoor occupations, together with the smaller sample sizes for outdoor workers, can introduce noise and bias estimates toward zero. Third, because baseline pain prevalence is already higher among outdoor workers—the mean prevalence is 21.3 % compared to 15.7 % among indoor workers—a ceiling effect may mechanically limit the detectable marginal impact of additional heat.

Even with these caveats in mind, the persistence of positive effects among indoor workers makes it unlikely that increased outdoor activity is the primary pathway linking heat and pain. Instead, the findings point to non-behavioural mechanisms—such as physiological strain or stress—that operate even when exposure to direct outdoor conditions is limited.

We further examine whether heat affects emotional states that could plausibly mediate the heat–pain relationship. Specifically, we re-estimate our baseline model using six daily emotional outcomes from

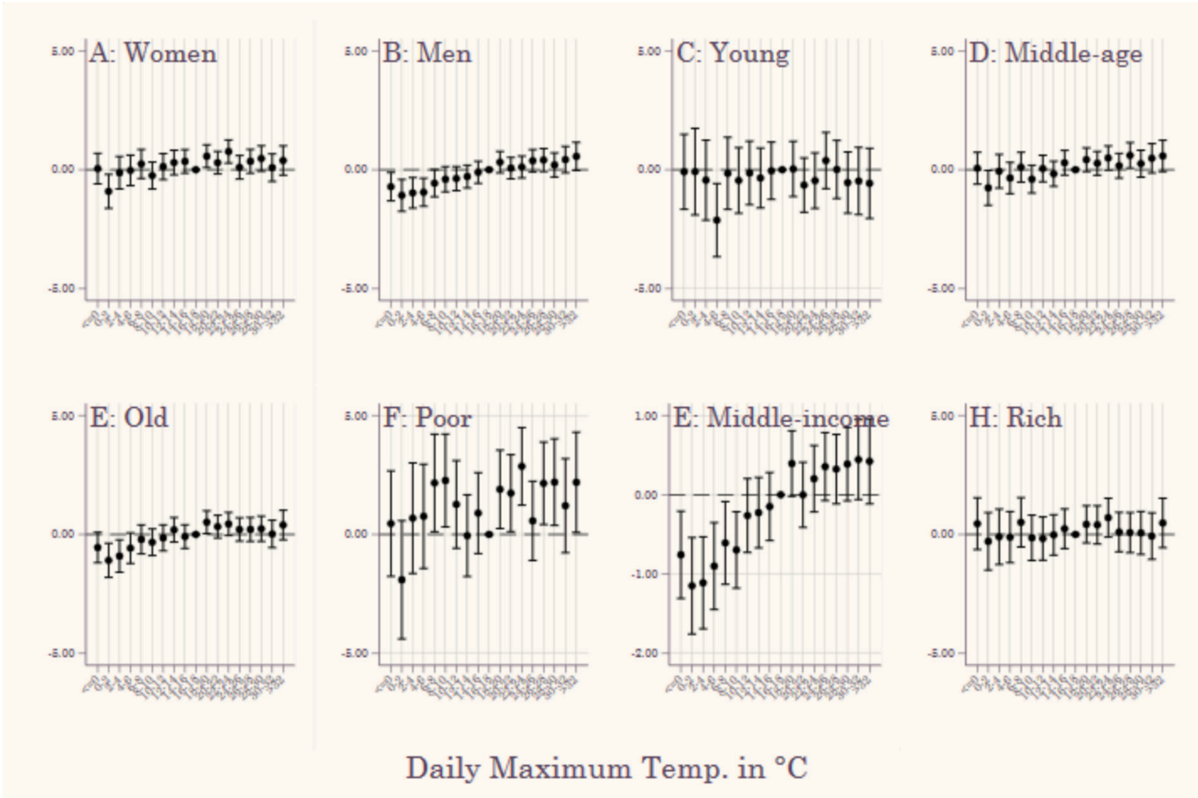

Fig. 4. The effects of heat (in 2-degree bins) on pain for different subgroups. Baseline group for comparison is 16–18 degrees Celsius. We report estimates for Women [N = 1,035,024], Men [N = 1,064,208], Young (≤ 25 years old) [N = 147,738], middle-aged (26 to 54 years old) [N = 849,559] and old (≥ 55 years old) [N = 1,116,829] respondents in Panels A, B, C, and D, respectively. We then report estimates for low-income (≤ $12,000/year) [$N$ = 128,158], middle-income ((> $12,000 but < $120,000/year) [N = 1,378,569] and high-income (≥ $120,000/year) [$N$ = 286,340] in Panel D, E, F, and G, respectively. All regressions follow our preferred empirical specification as explained in Fig. 2. 95 % confidence intervals, which are denoted by the tails, are constructed from standard errors clustered at the zip-code level. **Estimates are reported in columns 1 to 8 in Table S4 in the supplementary materials.**

the GHWI survey: (1) smiling/laughing, (2) happiness, (3) enjoyment, (4) stress, (5) worry, and (6) sadness. The results, shown in Fig. 6, reveal little systematic relationship between hotter days and positive emotions such as happiness, enjoyment, or smiling/laughing, nor with negative emotions like sadness or worry.

By contrast, stress emerges as the most consistently affected outcome. On days with maximum temperatures of 32 °C or higher, the probability of reporting stress rises by about 0.6 percentage points ($p < 0.05$). This effect is modest but statistically significant and in line with prior evidence linking heat exposure to heightened physiological and psychological strain (Obradovich et al., 2018; Mullins and White, 2019). The combination of higher stress and lower enjoyment (the latter falling by about 0.3 percentage points on hot days although this is imprecisely estimated) suggests that heat not only induces discomfort but may also exacerbate the perception and reporting of physical pain through heightened arousal and negative affect.

Taken together with the exercise and occupation analyses, these findings indicate that behavioural mechanisms (e.g., more outdoor activity) play a limited role, whereas non-behavioural pathways—particularly stress-related physiological and psychological responses—are more likely to account for the observed heat–pain relationship.

This distinction is also crucial for policy. If heat-related pain were mainly a behavioural issue, interventions could focus on reducing outdoor exertion. However, the continued effects among indoor workers, combined with increased stress on hot days, imply that interventions should also target physiological and psychological stress, such as improving access to cooling, enhancing sleep quality, or offering mental health support. Although tentative, these implications highlight why understanding mechanisms is vital for developing effective adaptation strategies.

4. Discussions and conclusions

Using matched meteorological and survey data from the Gallup-Healthways Well-Being Index (GHWI), this study provides new evidence on the relationship between temperature variations and physical pain among nearly 2 million individuals across the United States. We find that daily maximum temperatures of 32 °C or higher, compared to the baseline range of 16–18 °C, are associated with a 0.45 percentage point increase in the likelihood of experiencing pain—an approximate 1.9 % rise relative to baseline prevalence. Scaled to the national population, this corresponds to around 1.5 million additional people reporting pain on hot days. These findings suggest that heat is not only a threat to physical and mental health, as documented in prior research, but also to the lived experience of pain—a critical but underexplored dimension of well-being.

A central question is through which pathways temperature exerts its influence on pain. Two possibilities are debated in the literature: behavioural mechanisms, in which hotter days encourage outdoor activity that may lead to injury or discomfort, and non-behavioural mechanisms, in which heat directly heightens physiological strain or intensifies pain perception via stress and negative affect. Our analyses point more strongly to the latter. The persistence of heat–pain associations among indoor workers, coupled with evidence that hotter days are associated with elevated stress and reduced enjoyment, suggests that direct physiological or psychological pathways are more plausible than purely behavioural ones. This interpretation aligns with prior work showing that stress and thermal strain amplify pain perception (Wiech

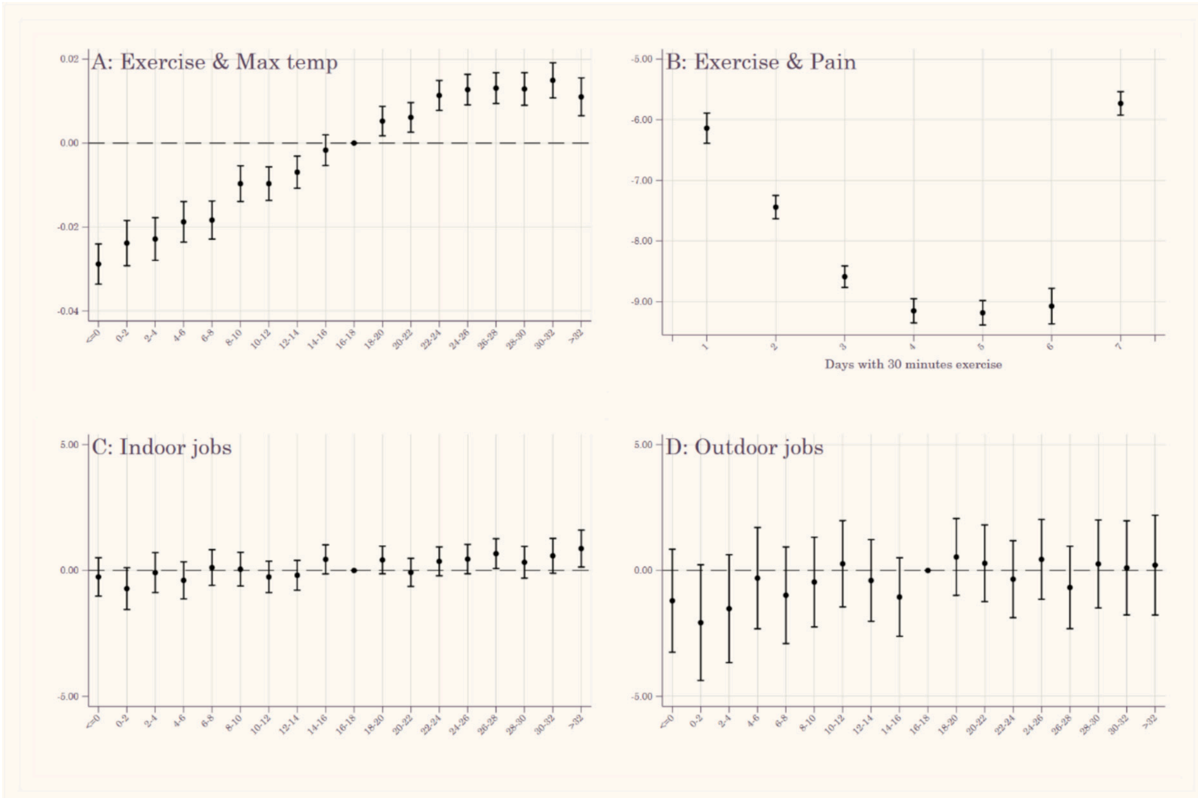

Fig. 5. Physiological explanations between heat & pain. Panel (A) reports the effects of heat on the probability of exercising for at least 30 min for at least one day in the last seven days. Panel (B) reports the effects of exercise intensity (number of days with >30 min of exercise) and the probability of physical pain. The baseline group for comparison is 0 days of exercise. Panel (C) and (D) reports the effects of heat (in 2-degree bins) on pain for respondents with Indoor [$N = 612{,}839$] and Outdoor [$N = 137{,}970$] jobs. We classify professionals (e.g lawyer, doctors), clerical, sales, managerial workers and business owners as indoor jobs, and classify construction, mining, manufacturing, farming and transportation workers as outdoor jobs. The baseline group for comparison is 16–18 degree Celsius for Panel (A), (C) and (D). All regressions follow our preferred empirical specification as explained in Fig. 2. 95 % confidence intervals, which are denoted by the tails, are constructed from standard errors clustered at zip-code level. **Estimates for Panel (C) and (D) are reported in columns 9 and 10 in Table S4 in supplementary materials.**

and Tracey, 2009; Obradovich et al., 2018; Mullins and White, 2019).

At the same time, the effects are not distributed evenly across the population. Middle-aged adults (25–54) and lower-income households experience the strongest associations, while effects are weaker for the elderly, likely reflecting avoidance of heat exposure. That the poorest households are most affected is consistent with limited access to adaptive investments such as air conditioning (Davis, 2015). These heterogeneous responses indicate that rising temperatures exacerbate not only the overall prevalence of pain but also the inequality of its burden.

Like all studies in the social sciences, this one has limitations. A key concern is the binary measure of pain ("*a lot of the day yesterday*"), which cannot capture gradations in intensity or duration. This introduces a ceiling effect: once respondents report pain, the measure cannot register "more pain." The plateau we observe at higher temperatures is therefore likely an artefact of survey design rather than the absence of additional physiological effects. As such, our estimates represent conservative lower bounds on the true welfare costs of extreme heat. Second, the GHWI does not differentiate between pain types (e.g., musculoskeletal vs headache) or sources (injury vs chronic condition), which constrains the interpretation of mechanisms. Third, while the U.S. context provides large-scale, high-quality data, it also represents a relatively wealthy country with widespread access to adaptive technologies. Effects may be larger in poorer countries with hotter climates and limited adaptive capacity, making generalisability an important area for further research (Carleton, 2017). Finally, variation in daily survey sample sizes across years (e.g., 1000 respondents per day in 2013, 500 in 2014, 1500 in 2017) could introduce noise; however, year and state-by-year fixed effects help mitigate this concern.

Despite these limitations, our findings emphasise the importance of recognising pain within the wider health impacts of climate change. Physical pain affects more than 1.5 billion people worldwide (Macchia, 2022) and is associated with increasing opioid use and deaths of despair (Case and Deaton, 2015). However, it has received little attention in climate–health research. By demonstrating a strong link between rising temperatures and increased pain, with effects likely understated by ceiling effects, especially among socioeconomically disadvantaged groups, this study highlights a new way through which climate change can worsen health inequalities. For policymakers, the findings suggest that strategies to reduce heat-related harms should address not only mortality and acute illnesses but also the more subtle, widespread burden of pain—a vital aspect of well-being central to human welfare.

CRediT authorship contribution statement

Cheng Keat Tang: Methodology, Investigation, Formal analysis, Writing – original draft. **Nattavudh Powdthavee:** Methodology, Conceptualization, Writing – original draft. **Lucía Macchia:** Resources, Writing – review & editing.

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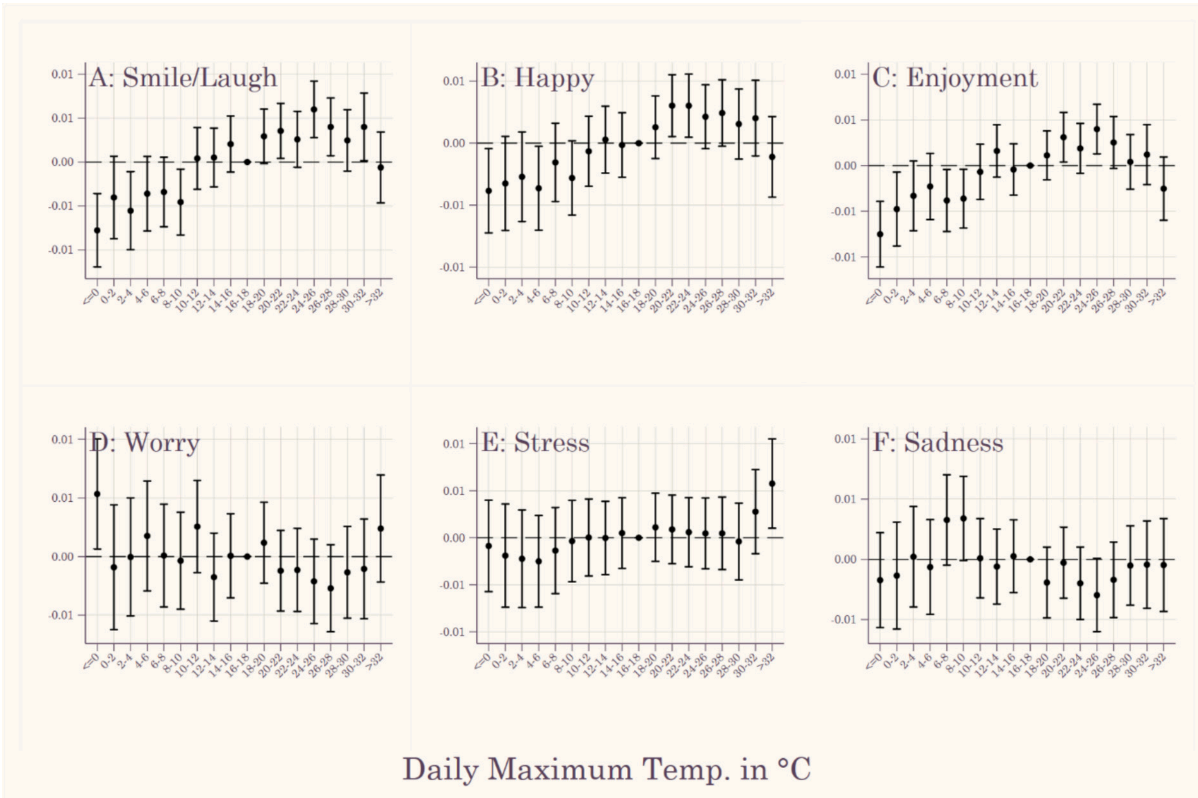

Fig. 6. Psychological explanations between heat & pain. The effects of heat (in 2-degree bins) on various emotional outcomes, including Panel (A). Smile/Laugh, Panel (B) Happy, Panel (C): Enjoyment, Panel (D): Worry, Panel (E): Stress and Panel (F): Sadness. All regressions follow our preferred empirical specification as explained in Fig. 2. 95 % confidence intervals, which are denoted by the tails, are constructed from standard errors clustered at the zip-code level. **Estimates are reported in Table S5 in the supplementary materials.**

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.

Data availability

The Gallup-Healthways Well-Being Index (GHWI) belongs to Gallup, Inc. For more information, see https://news.gallup.com/poll/246200/gallup-national-health-index-work.aspx). Scripts for analyses are available through the Open Science Framework (OSF) https://osf.io/28akn/?view_only=4efa590e30004fd09fc232a30123c4d1

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