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Extreme heat and heatwaves are linked to the risk of unintentional child injuries in Guangzhou city

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With unintentional injuries being the leading mortality cause among children, the comprehensive evaluation of the unintentional injury burden concerning heat exposure remains unknown. Here we quantified the years lived with disability (YLD) due to unintentional child injuries in Guangzhou from 2016–2020 using the injury surveillance data. A Poisson regression model was employed to explore how various magnitudes of heat exposure could increase the injury burden in different children's subgroups. Our findings suggest a positive link between heat exposure and childhood injuries. The successive heatwave led to a 16.8–23.8% higher risk of childhood injuries. Girls and preschoolers exhibited higher vulnerability to heat. Furthermore, heat exposure increased the road injury burden for preschoolers aged 3–6 years but not for adolescents. Our study links heat exposure to childhood unintentional injuries, providing insights into the demographic features and injury causes. This evidence can be used to inform healthy childhood development.

The escalating global average temperature, surging by 1.1 °C since the pre-industrial period, has marked recent years as the hottest on record[1]. The environmental heat intensifies the risks of adverse health events, elevating the burden of premature mortality and morbidity. Burkart et al. observed a staggering fourfold increase in heat-related mortality between 1990 and 2019, culminating in 365,000 deaths worldwide in 2019[2]. Unintentional injuries, among the range of heat-related illnesses, are gaining public health concerns due to their significant health burden[3,4]. Previous studies have indicated that heat exposure correlates with a 1.66-fold increased risk of death from unintentional injuries[5]. In particular, high temperatures may increase the risk of road injuries and falls, among various subtypes of injuries for the general population[3].

Yet, the health impact of heat exposure on injuries among children has not received adequate attention[6,7]. The American Academy of Pediatrics reported that unintentional injuries accounted for 40% of annual deaths among children under 18 years of age, marking it the leading cause of childhood death[8,9]. Children exhibit distinct behavioral and physiological traits that render them more vulnerable to environmental heat exposure compared to adults[7,10]. Their rapid growth and development, smaller physique, larger relative body surface area, and less robust core body temperature regulation may contribute to lower heat adaptability when compared to adults[11–13]. Simultaneously, the increased outdoor activity among children during hotter months amplifies climate-sensitive exposures[14,15]. Moreover, in warmer seasons, people generally wear lighter clothing and have exposed skin, further heightening vulnerability to heat exposure[16]. Children, with their higher levels of curiosity, activity frequencies, and inadequate self-protection skills, face an elevated risk of severe burns. Previous studies have indicated varying responses to heat exposure among children of different age groups as they undergo growth and development[10,17]. However, fewer studies have delved into elucidating the influence of heat exposure on unintentional injury burden in children subgroups, and even fewer have investigated its impact on different causes of injury in children. Identifying the health risks of child injury ascribed to heat exposure and providing evidence-based guidelines as well as practices

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applicable to children and their caregivers is of particular importance to the well-being and development of the children. Furthermore, the majority of current heat exposure studies have primarily focused on fatal outcomes of injuries, neglecting the underlying long-term comprehensive health loss of non-fatal unintentional injuries[5,18]. Given that unintentional injuries result in more childhood disabilities than fatalities, assessing the influence of heat exposure on non-fatal unintentional injuries in children holds great significance in mitigating the overall burden of such incidents.

The study hypothesized that heat exposure would greatly impact the comprehensive health loss due to non-fatal injuries in children and that certain subgroups, such as toddlers and children of older age, would manifest different vulnerabilities due to various injury epidemiological features. Specifically, we synthesized data from both outpatient and inpatient sources to quantify the comprehensive health loss of injuries while using the years lived with disability (YLD) as the main indicator. YLD can quantify the health burden of living with a non-fatal condition and has been widely implemented in the burden of injury study[19,20]. Furthermore, we conducted multiple stratified analyses to elucidate how distinct demographic characteristics and categories of injury might modify the effect estimates of heat exposure on the YLD burden in children.

Results

Descriptive statistics

Between May and September 2016–2020, there were 77 days classified as experiencing extreme heat, notably peaking in July (42 days). Over half of the 11 recorded heat waves took place in July, with the rest exclusively occurring in August (Table 1). The table delineating the burden of unintentional injuries among children in Guangzhou is outlined in Table S2, while Table S3 provides an overview of the meteorological factors.

The overall impact of heat exposure on the burden of childhood accidental injuries

Figure 1 presents whether higher temperature, extreme heat, and heat waves were associated with higher risks of childhood injury burden. By using the non-fatal YLD indicator, we found the association of heat waves with YLD burden of child injuries (relative risks [RR] = 1.171, 95% CI: 1.147–1.196) surpassed those observed in exposures to extreme heat (RR = 1.125, 95% CI: 1.106–1.145) and general ambient temperature (RR = 1.019, 95% CI: 1.017–1.022). Additionally, our observations indicate a correlation between higher injury risks and the duration of exposure to heatwaves, with a statistically significant effect from the second day onward (RR = 1.168, 95% CI: 1.121–1.218 for the second day and RR = 1.238, 95% CI: 1.205–1.271 for the third day or more). Figures S1–S3 depict the impact of general ambient temperature on the YLD burden of unintentional injuries among children, while Figure S4 captures the monotonic increasing trend for such an impact.

The associations stratified by injury causes and subgroups of children with different ages and sex

To understand if different levels of heat exposure would have varying effects on children stratified by various subgroup features, we further conducted the stratification analysis. The exposure to extreme heat was linked with a

Table 1 | The monthly distribution of extreme heat and heatwaves in Guangzhou from 2016 to 2020

Month	Extreme Heat (day)	Heatwaves
May	1	0
June	8	0
July	42	7
August	23	4
September	3	0
Total	77	11

Data source: Historical temperature data can be extracted from https://data.cma.cn.

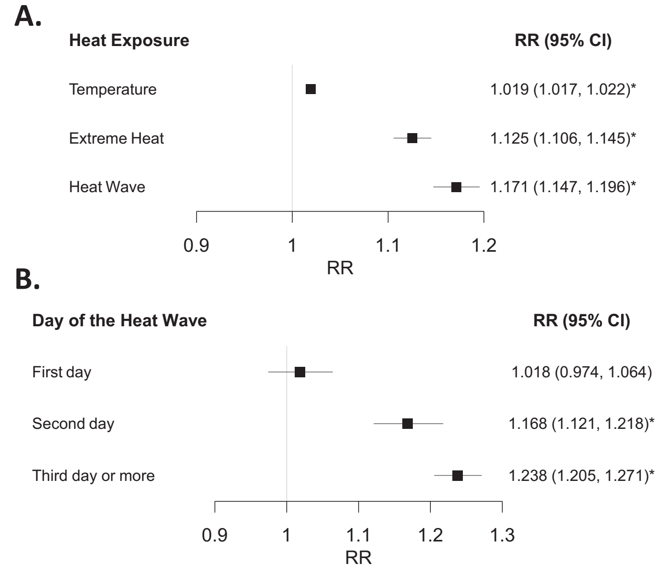

Fig. 1 | The relative risk (RR) and 95% confidence interval (CI) for childhood accidental Injuries following heat exposure and successive heatwaves. **A** shows the overall effect of varying magnitudes of heat exposure. For instance, the estimated relative risk of temperature represents the impact of each 1-unit increase in ambient temperature on the non-fatal burden of childhood accidental injuries. **B** shows the impact of heatwave duration on the non-fatal burden of childhood accidental injuries. The linerange indicates the confidence interval for each corresponding relative risk estimate.

respective 15.2% (95% CI: 12.6–17.9%) and 10.6% (95% CI: 7.3–13.9%) higher risk of YLD burden in children suffering falls and fire-related injuries, both causes of which were the most common. In contrast, heat waves played a more crucial role in road injuries (26.0% higher risks, 95% CI = 17.8–34.8%), as compared to falls (17.2% higher risks, 95% CI = 14.1–20.5%) and fire-related injuries (14.6% higher risks, 95% CI = 10.5–18.9%).

In terms of age subgroups, extreme heat might lead to a higher injury burden among children under 13 years, with the most substantial effects observed in those aged 3–6 years (RR = 1.207, 95%CI: 1.171–1.243). The impact of heat waves mirrors those of extreme heat, also leading to higher risks of injury burden in children aged 3–6 years (Fig. 2). However, when stratified by common injury causes and age subgroups as shown in Fig. 3, we found toddlers and children were indeed vulnerable to different causes of injury. For instance, extreme heat was associated with a maximum RR of 1.309 (95% CI: 1.148–1.492) in the 0–2 age group for road injuries. For fall injuries, the highest effect estimate was observed among the older children of 7–12 years of age (RR = 1.245, 95% CI: 1.177–1.317). Generally, exposure to heat waves was associated with a slightly higher risk of road injuries and falls among children under 12 years. As for the sex disparity, extreme heat significantly elevated the YLD burden of unintentional injuries in girls (RR = 1.163, 95% CI: 1.131–1.196), with higher effect estimates than those observed in their male counterparts (RR = 1.102, 95% CI: 1.078–1.127). Moreover, heatwaves exhibited the most substantial impact on boys suffering road injuries (RR = 1.327, 95% CI: 1.221–1.441) and girls suffering falls (RR = 1.416, 95% CI: 1.357–1.478) (Fig. 4).

Findings from sensitivity analysis

As revealed in Table S4, the effect estimates of heat exposure remain robust even after incorporating air pollutants as confounders and with various adjustments of the degrees of freedom in the model. With the additional case-crossover analysis (Table S5) based on the individual data, we found that the excessive risk of unintentional injuries in children following heat exposures reached between 5.2–19.8%. These comparable estimates suggest that the link between heat exposure and higher injury burden may be rather consistent among children.

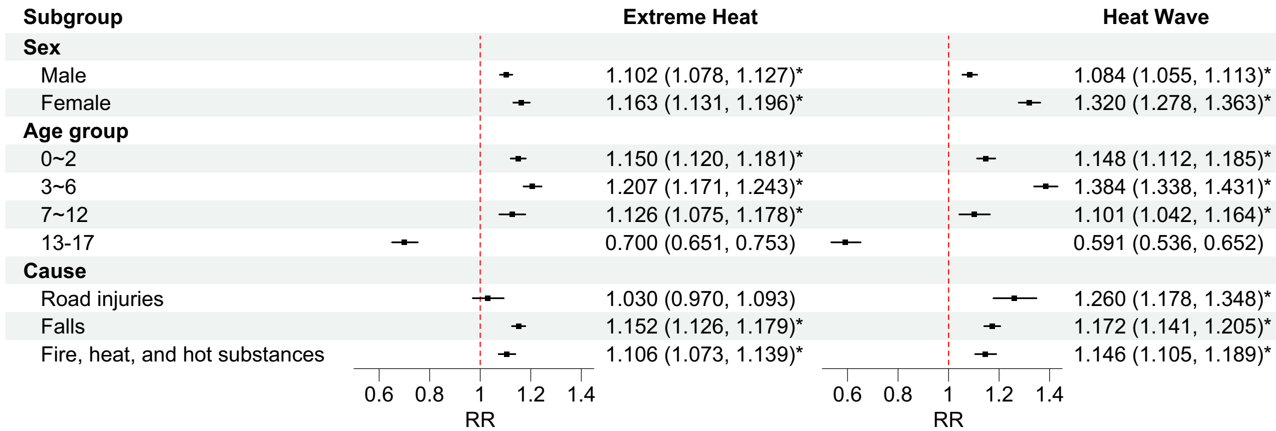

Fig. 2 | The impact of heat exposure on childhood injury burden, with children subgroups respectively categorized by age, sex, and cause of injury. The linerange indicates the confidence interval for the corresponding relative risk estimate. RR relative risk.

Overall, this study found that heat exposure was a potential risk factor for injury burden in children, with extreme heat elevating the non-fatal YLD burden by 12.5%, and heat waves by 17.1%. Younger children and girls were more vulnerable to heat exposure. During a typical heatwave, the risk of road injuries in preschoolers would increase by 1.668 times. Girls faced a 1.416-fold heightened risk of falls, whereas boys might experience a 1.327-fold higher risk of road injuries.

Discussion

This study underscores the significant implications of non-fatal unintentional injuries among children attributable to climate change. We demonstrated how various extreme weather events may impact childhood injury burden. Specifically, we revealed the vulnerable subgroup characteristics and injury causes that would be informative for injury prevention and heat mitigation. This study indicated that extreme heat was linked with a 12.5% higher risk of childhood injury burden, particularly for girls and children of 3–6 years of age. Intriguingly, the association between heat waves and the unintentional injury burden in children surpassed those observed in exposure to extreme heat and general ambient temperature, with the excessive risk of heat waves reaching 17.1%. These findings suggest the substantial influence of successive heatwaves on increasing the non-fatal burden of unintentional injuries among children. Additionally, heat exposure may lead to a variety of injury causes in children of different age groups and sex. This critical evidence may be incorporated in the prevention of injuries among children and further support heat mitigation, within the context of global warming.

Principal findings and comparison with previous studies

The escalating frequency and intensity of extreme heat events underscore the pressing need to protect children from heat-related injuries. Existing research has predominantly focused on the risk of non-accidental causes of mortality, i.e. disease-related mortality, among children during hot weather periods, despite the higher prevalence and consequential impact of unintentional injuries in children[17]. For instance, a survey conducted in Malaysia revealed a 9.1% increased overall risk of child mortality during heat waves. Yet, these prior studies seldom focused on injuries of unintentional natures[21]. Our findings unveiled a 12.5–17.1% increased risk of injury YLD among children during extreme weather events of heat waves. Furthermore, we observed a 23.8% increase in the risk of childhood injury burden on the third day and a 16.8% increase on the second day, both following the onset of the heat wave. Together with a few previous publications[22] suggesting the lag effects of heat waves on non-accidental mortality, our findings on unintentional injuries may contribute to the pool of evidence concerning the protection of vulnerable children subgroups against successive heat waves.

Next, our findings indicate that girls face a higher risk of injury during heatwaves, when compared to boys. Notably, girls exhibited an elevated vulnerability to fall-related injuries amidst heat waves, while boys demonstrated an increased risk of road injuries during these adverse weather events. These findings may be similar to those from a U.S. study, which reported a 2.3 times higher risk of heat-related emergency department visits in girls[6]. Based on a limited number of studies on preadolescent children[23,24], we suspect that girls may have a lower sweat rate than boys of equal fitness and size, and may have a weaker capacity for acclimation. These biological factors may explain their disadvantages in hot-dry environments.

We also noted that heat waves were significantly associated with unintentional injuries among the early preschoolers (3–6 years of age), with an excessive risk of 38.4% and surpassing those observed in the other age groups. Conversely, we found no observable impact on older adolescent groups (13–17 years old). These findings were similar to several studies investigating the effects of heat exposure on emergency department visits among children of younger age. For instance, Sheffield et.al. reported a 2.6% excessive risk of emergency department visits associated with heat events among children under 4 years[10]. With this solid evidence and much higher effect estimates, we advocate the need for designing and offering comprehensive education programs targeting parents and caregivers to enhance their knowledge and capabilities in safeguarding young children against heat-related unintentional injuries.

Within the context of heat exposure, the non-fatal burden of unintentional injuries varied by different causes[25,26]. We found that heat waves significantly increased the injury burden ascribed to falls and burns while exerting an even higher risk of road-related injuries. Hussain et al. documented that heat waves led to an increase in the occurrences of children falling from windows[27,28]. Their study highlights the implementation of window-guarding legislation would notably reduce the incidence of window falls among children. Another study by Hou et al. reported a 1 °C rise in average daily temperature may be linked to a 1.58% escalation in the risk of motor vehicle crashes[29]. As far as our knowledge extends, there exists a paucity of studies examining the cause-specific non-fatal YLD burden of childhood injury associated with heat waves.

Interpretation of the evidence and its implications for childhood development

Firstly, the exacerbated risk associated with heat waves, as compared to general ambient temperature or extreme heat exposure, could potentially be attributed to the prolonged and intense nature of heat waves[30,31]. Indeed, children may lack the adaptive capacities to mitigate against adverse heatwaves in the short-term[32]. Regarding the long-term consequences of heat-related childhood injuries, physical integrity[33], mental wellness[34], cognitive functions[35], social development[36], and socioeconomic status[37] may also be

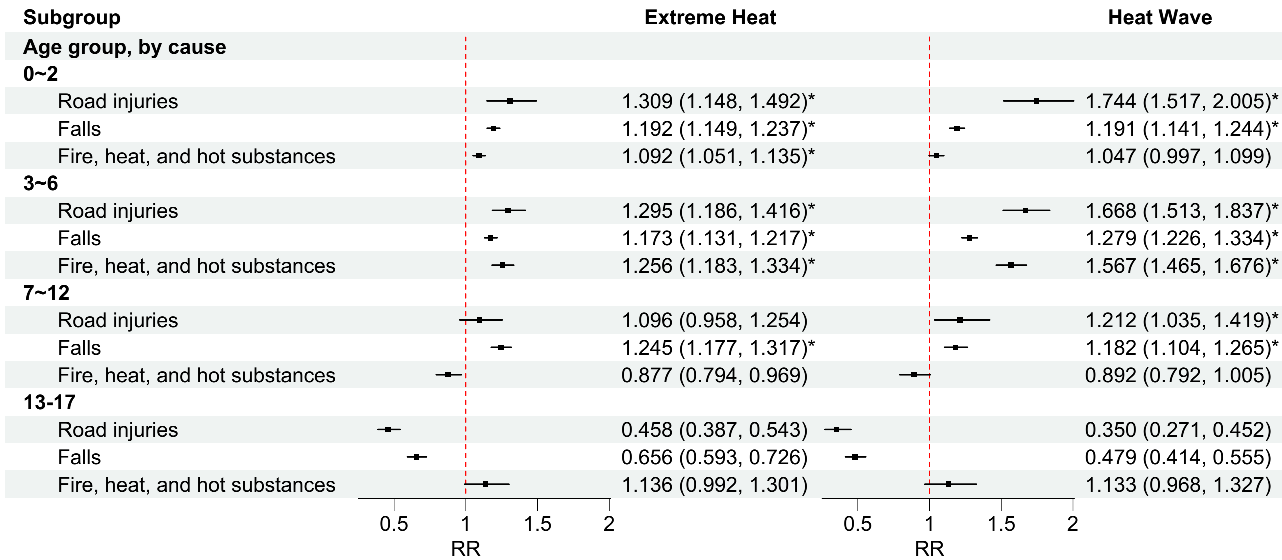

Fig. 3 | The influence of heat exposure on childhood injury burden, simultaneously stratified by injury causes and diverse age subgroups. The linerange indicates the confidence interval for the corresponding relative risk estimate. RR relative risk.

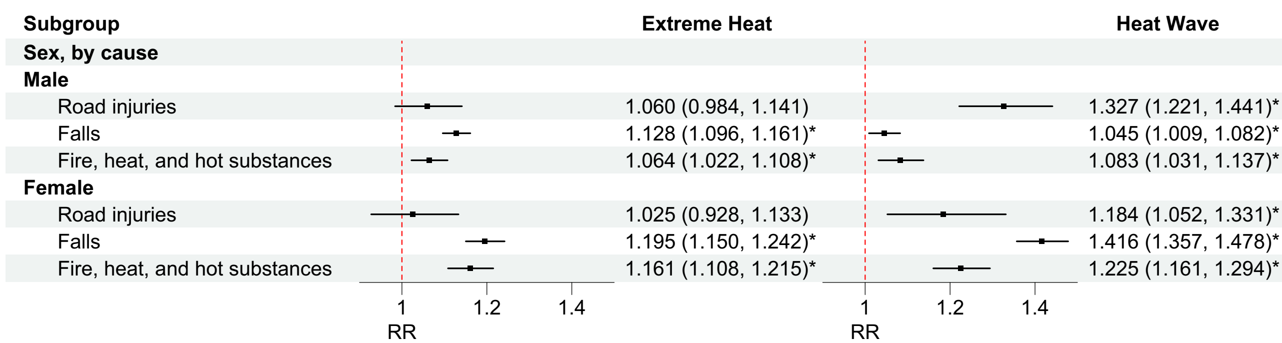

Fig. 4 | The influence of heat exposure on childhood injury burden, as stratified both by injury causes and sex. The linerange indicates the confidence interval for the corresponding relative risk estimate. RR relative risk.

impaired. Combined with previous studies, our study shall underscore the imperative need for collaborative efforts among government, communities, and child caregivers to develop and implement comprehensive strategies aimed at safeguarding children from heat-related injuries. Moreover, initiatives directed at curbing greenhouse gas emissions[38] as well as fostering the creation of greener, safer, and healthier living environments[39] may be promising in mitigating the adverse impacts of heat exposure.

Secondly, preschoolers face a greater risk of injury during a heatwave. The underlying explanations may be linked to their less-developed thermoregulatory systems and lower cardiac output[17]. These factors could lead to a lower physiological ability to adapt to successive heat waves. Additionally, the tendency to rely on grow-ups among preschoolers for protection and care may be another contributing factor to their lower heat wave adaptability[40]. Considering the growing ability of self-protection and knowledge attainment, extreme heat seems to have a diminished impact on adolescents. Therefore, to alleviate the burden of heat-related injuries among children, age-specific strategies in injury prevention are essential. On the one hand, enhancing parental supervision and bolstering community-level protection infrastructure as well as facilities are pivotal in protecting preschoolers from unintentional injuries. On the other hand, for school-aged children, we advocate for strengthening injury prevention programs and knowledge promotion among school faculties, optimizing institutional infrastructure and facilities, and fostering an environment conducive to injury reduction. Besides, the vulnerabilities to heat exposure among girls and children of younger age groups may warrant more dedicated research to further explore the biometeorological mechanisms[41] and possible protection measures[42]. Nevertheless, our study still provides essential support for government policy-making and child protection against heat exposure.

Thirdly, the link between heat exposure and various injury causes can be comprehended through several rationales. Regarding road injuries, one plausible explanation involves heat stress-induced dysfunction of 5-hydroxytryptamine[43]. This biological pathway may lead to a more severe state of mental aggression, weaker judgment of self-protection, and diminished driving proficiency, contributing to the higher risk of road accidents[44]. As for fall injuries, previous publications suggest that rising temperatures prompt children to spend more time outdoors, which may significantly increase the likelihood of fall-related incidents[15]. Another viable explanation may be ascribed to the comparatively lower heat resilience among children, as compared to adults. The weaker heat resilience may increase the chance of dehydration and electrolyte imbalances in hot weather, consequently elevating the risk of fall injuries[6]. For fire-related injuries among children, a few key rationales may be considered: (a) the tendency to wear scanty and thin clothing, not able to protect against thermal injuries[45], (b) the increased skin exposure to various heat sources, such as performing outdoor activities under burning sunlight[9], and (c) the limited self-protection awareness during heat waves[46]. These common factors may, when combined, contribute to the higher possibility of severe burns during extreme heat events.

These findings emphasize the necessity of considering children's safety during heat waves. Integrating heat wave alerts into early warning systems or programs on injury prevention[5,32] can assist caregivers in implementing necessary protective measures during extreme heat events. These measures may encompass limiting outdoor activities and adopting sunlight protection[47]. In terms of road safety, the knowledge of the correct use of helmets and child safety seats should be promoted[48]. The authorities should focus on protecting vulnerable children subgroups by raising public investment in injury-prevention infrastructure, promoting public awareness through targeted health programs, and developing interventions as well as support systems to safeguard the children's well-being[49,50]. In addition, the educational institutions and the communities need to establish a safer built environment[51], creating urban green play spaces with proper blue space settings[52,53], mandating guidance and protocols for addressing extreme heat events[32], and so forth. These heat-health action plans may help regulate the urban climate and contribute to preventing heat-related injuries among children[54].

Strength and limitation

This study exhibits several strengths. Firstly, to the best of our knowledge, it stands as one of the few attempts to assess the comparative risks of both heat exposure and heatwaves on the burden of non-fatal injury, while measuring such burden using the comprehensive non-fatal YLD indicator. This pioneering effort offers an applicable framework for policy-makers and health practitioners to conduct similar studies in other regions. Secondly, this research consolidates the evidence on the significant impacts of heat exposure concerning children's injury vulnerabilities, providing a clearer path for protecting those in utmost need. In particular, the findings concerning road and fall injuries may furnish valuable insights for policy formulation and preventive strategies. Thirdly, the generalized modeling approach with spline functions adeptly controlled for time-related confounders, such as days of the week and holidays. This method ensures a more accurate assessment of the impact of heat exposure on injury burden.

This study also has some limitations. For instance, we did not account for potential confounders such as parental occupation, literacy level, and other pertinent factors. The absence of this information in the monitoring database restricted us from adjusting for these confounders. Nonetheless, we conducted validation analyses using a case-crossover design (Table S5), which should effectively control for the influence of unknown confounders[55]. While the effect estimates of heat exposure on childhood injury remain consistent and comparable throughout the main and validation analyses, future studies with a proper experimental design[56] may be needed to account for the different sets of confounders to confirm the causal link. Next, the study is based on data from a megacity located in the subtropical region. The findings might not be directly generalizable to other regions with different climate features and demographics. Yet, our findings still add to the pool of evidence reassuring the comprehensive loss of health due to heat-related injuries. These key aspects can be used as a crucial reference for preventing heat exposure among children living in subtropical regions, which will benefit long-term healthy childhood development.

Conclusions

The underlying impact of heat-related unintentional injuries on the long-term development and well-being of children may be complicated and extensive. Our study suggests a notable 12.5–17.1% escalation in the non-fatal burden of unintentional injuries among children during various magnitudes of heat events. Remarkably, we observed higher vulnerability to heat exposure among girls and preschoolers, and found higher risks for heatwave-related road accidents. These findings may shed light on how to protect children living in subtropical regions against heat exposure. Indeed, comprehensive protection strategies, such as raising public investment in injury-prevention infrastructure, promoting public awareness campaigns, tailoring targeted interventions for the vulnerable subgroups, and developing heat-prevention action plans, may help to reduce the non-fatal burden of unintentional injuries attributable to heat exposure for children. In addition, the authorities and relevant stakeholders such as the educational institutions need to strengthen health education programs to improve the self-protection ability among school-aged children and to establish injury-preventive environments with green and blue spaces. Finally, our study may support the establishment of policies aiming at healthy childhood development, and in particular, extend the knowledge on how to alleviate the non-fatal injury burden via heat mitigation. This would have a broad implication for addressing the health challenge of climate change.

Methods

Calculating the injury-related YLDs

The calculation of YLD of injury consists of three steps: (a) collecting data on the incidence of injury and choosing cases to include, (b) dividing cases into different injury categories, and (c) combining the subgroup incidence data with related disability weights, durations, and proportions of long-term disability[57].

We included cases of injury recorded by emergency-department-based injury surveillance systems in Guangzhou during 2016–2020. To account for the summer season, we only selected injury cases under the age of 18 years occurring between May and September during each year. Then, we decomposed the cases by injury cause and type, following the codes of the International Classification of Diseases, tenth revision (ICD-10). We referred to the Global Burden of Disease study for parameters such as disability weights, case duration, and proportions of long-term disability, and considered parameters in different scenarios concerning injury cases admitted to emergency departments and those hospitalized[25]. Incidence-based YLDs were calculated by multiplying the injury incidences by their duration and their disability weights. Following the indirect method of calculating the burden of disease, we redistributed years of life lost due to premature death from injuries in the whole city (YLL_{tot}) by the ratio of sentinel-based YLD_{sen} and YLL_{sen} using

$$YLD_{tot} = YLL_{tot} * YLD_{sen} / YLL_{sen} \tag{1}$$

The redistribution process is necessary due to the unavailability of complete data on the incidence of injuries concerning the whole city[58].

Meteorological variable as the main exposure

The daily average meteorological data for the summer months (May to September) of Guangzhou from 2016 to 2020 were obtained from the China Meteorological Data Sharing Service System (https://data.cma.cn)[59]. We extracted average ambient temperature (°C), humidity (%), cloud amount (unit-free), and air pressure (pa) from the official monitoring stations and derived the city-level daily meteorological data. In addition, temperature above the 90th percentile during the summer months of 2016–2020 was defined as extreme heat, and additionally, extreme heat with a duration of at least three days was defined as the occurrence of a heat wave.

Statistical analyses

The Poisson generalized linear model was used to estimate the effects of heat exposure on the YLD burden of non-fatal injury among children, following a few prior studies[60]. We used the Akaike information criterion (AIC) for model selection, as it weighs the trade-off between goodness-of-fit and model complexity and could address issues of underfitting. We selected the model with the lowest AIC as the best model. The deviance residual was then used to comprehensively validate the goodness-of-fit of the models[61]. Specifically, it can provide an indication of the model's adequacy. The model would be appropriate and unbiased if the median residual is close to zero (Table S1). In addition to temperature, the model also included humidity, cloud amount, and air pressure with 3 degrees of freedom, as follows:

$$\widehat{YLD} \sim Poisson(\lambda) \tag{2}$$

$$\begin{aligned}\lambda = & Temperature + ns(humidity, 3) + ns(Air\ pressure, 3) \\ & + ns(Cloudamount, 3) + DOW + Holiday + ns(time, 5) + year\end{aligned} \tag{3}$$

Where the *ns* (*time*,5) and *year* represent natural spline function with 5 degrees of freedom per year to control long-term trends, *DOW* was used to control the effect of the day of the week; *Holiday* was used to control effect of the holiday. Natural spline function was also applied to the continuous temperature variable to capture the potential dose-response curve for the impact.

We separately examined the effects of ambient temperature, extreme heat, and heat waves on the burden of non-fatal injury among children. Besides, we evaluated the effects of the initial, second, and third days of the heatwave on the comprehensive health loss of unintentional injuries among children, respectively. We stratified the effect estimates of heat exposure on YLD burden by age, sex, and injury causes. The stratification analysis captured the potential vulnerabilities due to different injury causes and subgroup features among children.

Sensitivity analysis

We performed multiple sensitivity analyses by altering the modeling degrees of freedom and by introducing air pollution variables as confounders. Specifically, in investigating potential confounding effects from air pollution, we considered common pollutants such as $PM_{2.5}$ and O_3 and employed normal splines with three degrees of freedom. We then established the Poisson models based on the overall children population and various subgroups (i.e., age groups, sex, and injury causes). We incorporated the case-crossover analysis[55,62] using the individual surveillance data to further validate the adjusted effect estimates of heat exposure on unintentional injuries.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Historical daily meteorological data is freely available at: https://data.cma.cn. Underlying data for the manuscript figures are available as Excel files on the Zenodo repository and can be accessed at: https://doi.org/10.5281/zenodo.12820167[63].

Code availability

The code used to produce the effect estimates is available on request from the corresponding author.

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Author contributions

T.T, B.H.L, and Y.C.Z performed the data analyses and figure production, and contributed substantially to writing the initial and the revised final manuscripts. X.L., Y.T.H., and P.Z.Q led project planning and funding acquisition and contributed to writing the initial and final manuscripts. Data acquisition and interpretation were conducted by T.Y.H, B.H.L, C.X.S, and P.Y.W, all of who contributed to writing the initial and final manuscripts. S.M.C, T.G., Z.Q.L, and W.J.Z participated in data analyses and drafted the work. All authors contributed to the review and editing, and have approved the submitted version.

Competing interests

The authors declare no competing interests.

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