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Evaluation of the Impact of Ambient Temperatures on Occupational Injuries in Spain

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Background: Extreme cold and heat have been linked to an increased risk of occupational injuries. However, the evidence is still limited to a small number of studies of people with relatively few injuries and with a limited geographic extent, and the corresponding economic effect has not been studied in detail.

Objectives: We assessed the relationship between ambient temperatures and occupational injuries in Spain along with its economic effect.

Methods: The daily number of occupational injuries that caused at least one day of leave and the daily maximum temperature were obtained for each Spanish province for the years 1994–2013. We estimated temperature–injuries associations with distributed lag nonlinear models, and then pooled the results using a multivariate meta-regression model. We calculated the number of injuries attributable to cold and heat, the corresponding workdays lost, and the resulting economic effect.

Results: The study included 15,992,310 occupational injuries. Overall, 2.72% [95% confidence interval (CI): 2.44–2.97] of all occupational injuries were attributed to nonoptimal ambient temperatures, with moderate heat accounting for the highest fraction. This finding corresponds to an estimated 0.67 million (95% CI: 0.60–0.73) person-days of work lost every year in Spain due to temperature, or an annual average of 42 d per 1,000 workers. The estimated annual economic burden is €370 million, or 0.03% of Spain's GDP (€2,015).

Conclusions: Our findings suggest that extreme ambient temperatures increased the risk of occupational injuries, with substantial estimated health and economic costs. These results call for public health interventions to protect workers in the context of climate change. https://doi.org/10.1289/EHP2590

Introduction

The health effects of temperatures have been extensively studied, particularly regarding mortality and morbidity (Basu 2009; Gasparrini et al. 2015b). A study conducted in 13 countries estimated that 7.29% of total mortality can be attributable to cold temperatures and 0.42% to heat (Gasparrini et al. 2015b). So far, the majority of the studies have considered counts of deaths, hospitalizations, or emergency visits as a health indicator.

Extreme ambient heat has important consequences also in the occupational sector, with some studies reporting important losses in work capacity and productivity linked to climate warming, with associated costs amounting to between 0.1% and 0.5% of GDP (Kjellstrom et al. 2016; Zander et al. 2015; Dunne et al. 2013; Hübler et al. 2008). Extreme heat, however, can have additional consequences in the occupational sector, for example, through increasing the risk of suffering occupational injuries. Some studies have suggested this link, also applicable to cold temperatures, but the evidence is still limited to a small number of studies with participants who experienced relatively few injuries and with a limited geographic extent (Bonafede et al. 2016). Large new studies are needed to confirm these results and calculate the potentially substantial associated burden on society. The costs associated with injuries attributable to cold and heat have not been accounted for in previous economic assessments of the potential impact of climate change in the occupational sector.

Several mechanisms are thought to underlie the link between ambient temperatures and risk of injury in the workplace. Exposure to high temperatures can lead to physiological and psychological changes associated with heat strain, which in turn can decrease workers' performance and lead to impaired concentration, increased distractibility, and fatigue (Kjellstrom et al. 2016). These factors increase the risk of occupational injuries. Similarly, factors related to working in cold environments, such as thermal discomfort, hypothermia, or reduced mobility while wearing protective clothing are associated with decreased dexterity and performance among workers, which can also trigger occupational injuries (Schulte and Chun 2009; Mäkinen and Hassi 2009; Rodahl 2003).

Current projections estimate an increase in worldwide surface temperature due to climate change (IPCC 2014). In its last assessment report, the Intergovernmental Panel on Climate Change (IPCC) highlights that heat waves will increase in frequency, intensity, and duration (IPCC 2014). Increases in temperatures may vary in different regions. Indeed, in some parts of the world, it is expected to be unsafe to work outside during some months of the year (Kjellstrom et al. 2016). This might be particularly critical in the Mediterranean region, where projections indicate summer warming of between 0.6°C and 1.5°C by 2050 (IPCC 2014). Even though ambient temperature is expected to increase in the upcoming decades, low temperature extremes (cold spells and frost days) will continue to happen (IPCC 2014), but less frequently.

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Despite their potential importance, so far neither the proportion of work injuries nor the number of lost working days attributable to ambient temperatures has been quantified. Therefore, we conducted a countrywide study in Spain to examine the relationship between ambient temperatures and occupational injuries, its variation according to workers' characteristics, and its associated economic costs.

Methods

Setting

This study was carried out in Spain, a country with a population of 46.5 million living in 50 provinces (excluding Ceuta and Melilla in North Africa). The predominant climate in Spain is Mediterranean, with dry, hot summers and winters with balanced temperatures and low rainfall. Other climates include oceanic (northwest), arid, and semi-arid (southwest), subtropical (Canary Islands), and continental climate (mountain ranges). The study period covered 20 y from 1994 to 2013.

Occupational Injuries

We collected daily data on occupational injuries that occurred during the study period and that resulted in at least one day of sick leave. Data were obtained from the Spanish National System provided by the Spanish Labour Administration. It is mandatory for companies to register all occupational injuries from formal employment to this registry. We excluded relapses and injuries that occurred during commuting, and we did include all injuries regardless of their severity (whether fatal or not). This registry provides data on sex, age, nationality (since 2003), type of contract, company's economic sector, type of injury, duration of sick leave, and worker's occupational class (according to the National Classification of Occupations, versions 1994 and 2011). We selected specific economic sectors for investigation based on previous research (Xiang et al. 2014a; Adam-Poupart et al. 2015). It was not possible to separate occupational injuries according to indoor and outdoor activities due to the lack of the typology of work carried out by workers.

Weather Data

Data on daily maximum and minimum temperature were obtained for each provincial capital from the European Climate Assessment & Dataset (European Climate Assessment & Dataset 2016). Temperature data of one single weather station were assigned to all occupational injuries that occurred in each municipality of the province. Missing values (0.01% of the data) were imputed considering: 1) the mean temperature registered on the day after and before the missing day, if only one value was omitted; or 2) the temperature registered in the most correlated station for the same day-month-year, if more than two consecutive days were missing. Our main results did not change if missing values were excluded (data not shown).

Economic Data

Our economic analyses were based on a previous study on the costs of occupational injuries in the Catalonia region of Spain (Abiuso and Serra 2008). That study provided estimates of the costs of occupational injuries in 2006 and 2007, and it divided them according to a) costs associated with maintaining production (including overtime payments and costs of replacement and training), b) long-term lost incomes (total income lost when a worker suffers an injury and cannot come back to work), c) health costs associated with costs of treatment and rehabilitation, and d) costs of pain and suffering (level of disability). The last category uses estimates of the value of a human life based on Riera et al. (2007), and a disability index based on Mathers et al. (2001).

Statistical Analysis

We used distributed lag nonlinear models to model the association between daily temperature and the daily number of occupational injuries. This methodology has been described previously (Gasparrini 2014). Briefly, these models allow us to describe complex nonlinear relationships and lagged dependencies by combining two functions describing the exposure–response association and the lag–response relationship. In the first stage of the analysis, we fitted a separate time series quasi-Poisson regression model for each province to estimate the specific temperature-injury association, reported as percent difference. The exposure–response association was modeled using a quadratic B-spline with one internal knot placed at the 50th percentile. We extended the lag period to up to 4 d using unconstrained distributed lags to include possible long delays in the effects of temperature. We used sensitivity analyses to test these modeling choices (Supplemental Material, Table S3). To control for seasonality and long-term trends, we included in the generalized linear model a natural cubic B-spline of time with eight degrees of freedom per year, an indicator of day of the week, holidays, month, and the number of workers registered in the social security system (included as an offset term). The results of this stage were cumulated over all lags to obtain the overall temperature–injuries association. Figures describing the results for this stage were constructed on a relative scale (Gasparrini et al. 2012), and they can be interpreted as the cumulative risk of having an occupational injury up to four days after the exposure for each degree Celsius increase in maximum temperature.

In the second stage of the analysis, we pooled the estimated location-specific associations using a multivariate meta-regression model. The pooled curve was used to define the temperature percentile of minimum occupational injuries (PMOI). We then summarized the results of the overall curve by computing the relative risk at the first and 99th percentiles using the PMOI as the reference, reported as extreme cold and extreme heat effects, respectively. The results were reported as percent differences.

All analyses were stratified by sex, age, nationality, type of contract, economic sector, type of injury, duration of sick leave, and worker's occupational class. Differences between groups were tested using multivariate Wald tests (Gasparrini et al. 2015a). To test the effect of changes in workplace regulations, we also stratified the analysis in two periods. To do so, we considered the year 2000 as the cutoff point due to the implementation of occupational injury prevention programs. As some studies reported a significant decrease in occupational injury rates after the implementation of these plans (Benavides et al. 2009), the two periods considered were 1994–2000 and 2001–2013.

To calculate the attributable measures (number and percentage of injuries due to nonoptimal temperatures), we used, for each day of the series and province, the overall cumulative Relative Risk corresponding to each daily temperature. Then, we calculated the total attributable number of occupational injuries due to nonoptimal temperatures by summing the results for all days of the series (Gasparrini et al. 2015b). The attributable fraction corresponds to the ratio between the attributable and total number of occupational injuries. We calculated heat and cold fractions by summing the series for days with temperatures above and below the PMOI, respectively. We also computed moderate and extreme impacts, in which extreme cold and heat were defined as temperatures below the 2.5th and above the 97.5th percentiles, respectively, in line with previous studies (Gasparrini et al. 2015b). Empirical confidence intervals were reported using Monte Carlo simulations (Gasparrini et al. 2015b).

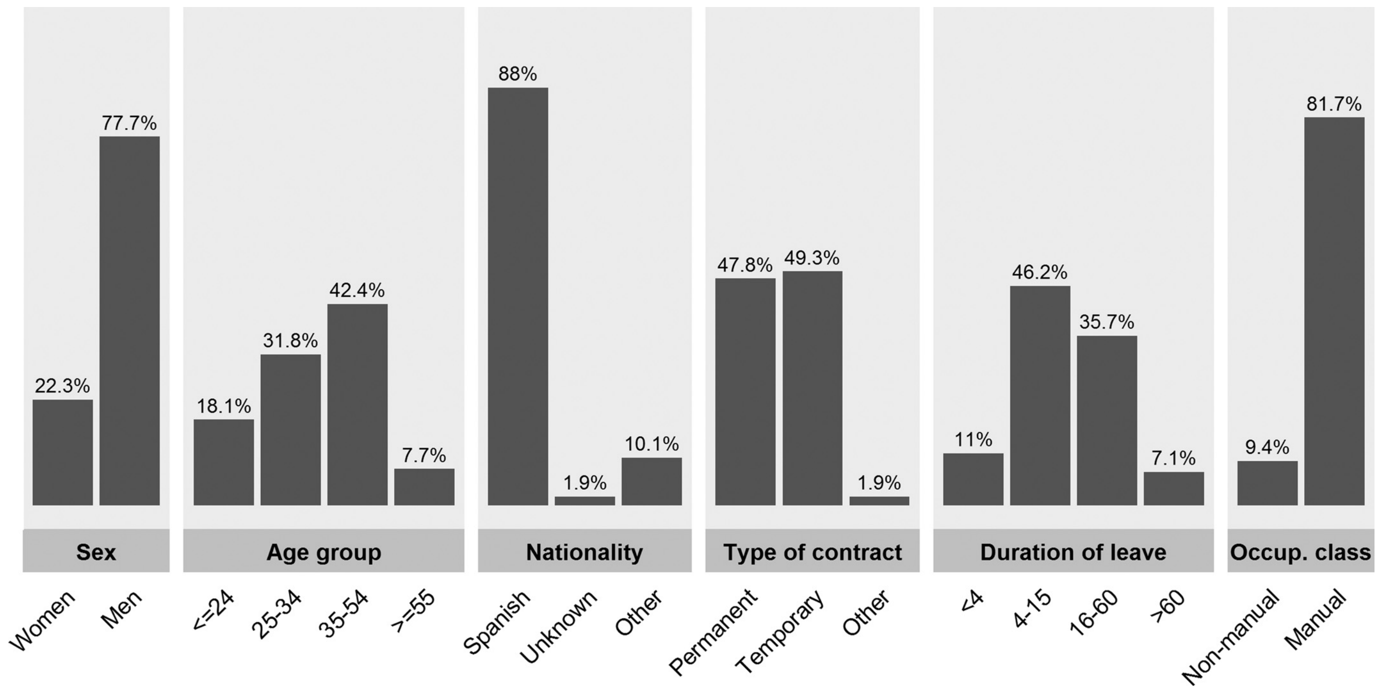

Figure 1. Descriptive statistics of workers that have suffered an occupational injury. Spain, 1994–2013. The percentages correspond to the distributions of occupational injuries within each category. The data were obtained from the Spanish National System provided by the Spanish Labour Administration.

We calculated the number of working days lost as a result of nonoptimal temperatures by considering the empirical distribution of the number of days of sick leave for each category of leave duration and the attributable number for both cold and heat. Finally, we calculated the economic cost of working at extreme temperatures. We first estimated the cost of each lost workday due to injury using the results of our study. Then, we multiplied this by the total number of workdays lost due to nonoptimal temperatures (previously estimated in our study) to obtain the total economic cost due to nonoptimal temperatures per year. We reported the results separately for cold and heat, expressed in Euro value for 2015 (according to changes in the Spanish consumer price index).All analyses were performed with R software (version 3.3.3).

This project has been approved by the Clinical Research Ethics Committee of the Parc de Salut MAR (November 2014).

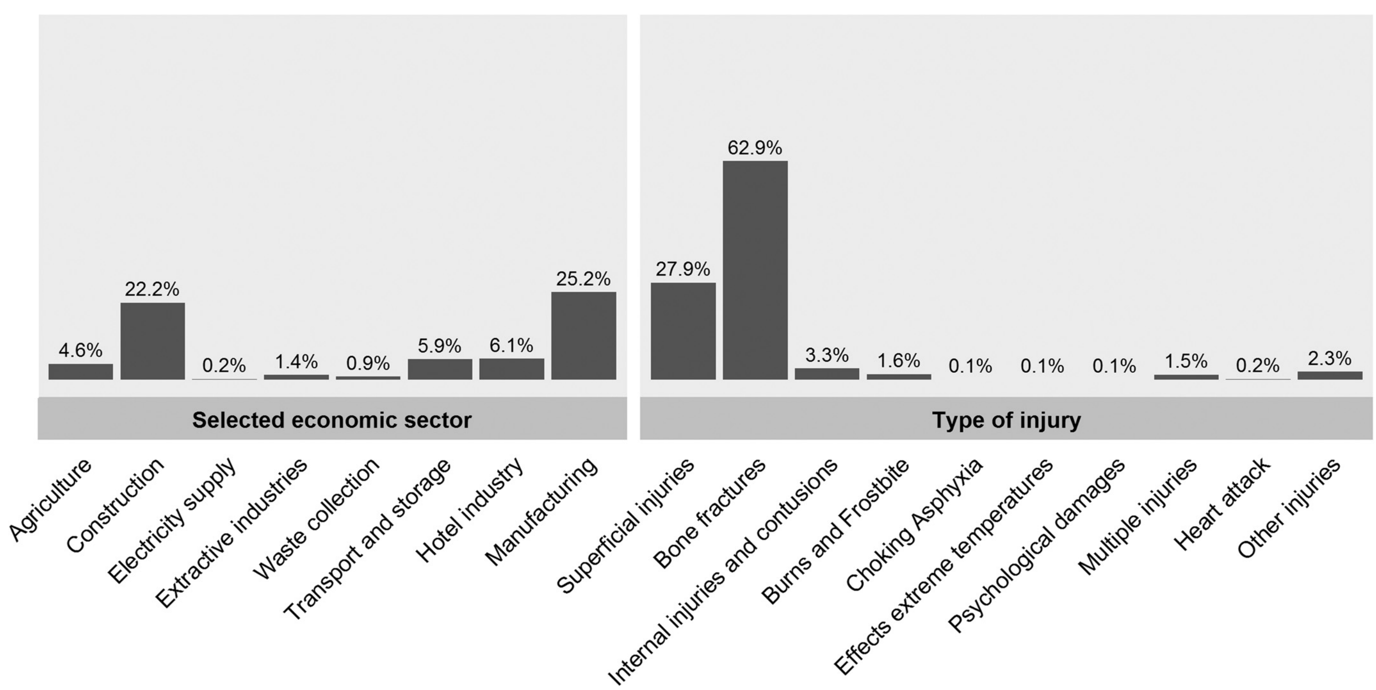

Figure 2. Descriptive statistics of workers that have suffered an occupational injury. Spain, 1994–2013. The percentages correspond to the distributions of occupational injuries within each category. The data were obtained from the Spanish National System provided by the Spanish Labour Administration.

Data Sharing

The meteorological data used in this study is publicly available at http://www.ecad.eu. The occupational data that support the findings of this study are available from the Spanish Labour Administration, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. However, data are available from the authors upon reasonable request and with permission of the Spanish Labour Administration. The R code used is available at https://github.com/ericamartinez/Temperatures_occupational-injuries.

Results

The study included all 15,992,310 occupational injuries reported in Spain between 1994 and 2013. These injuries occurred at a rate of 50 injuries per 1,000 workers per year, and an average of 2,189 injuries per day. The two provinces with the largest cities —— Madrid and Barcelona —— had a mean of more than 300 injuries per day, but accounted for only 28.6% of all injuries included in the study (Supplemental Material, Table S1). Most injuries (91%) were bone fractures or superficial injuries, and 47% occurred in the construction and manufacturing sectors (Figures 1, 2 and Supplemental Material, Table S4). Our study area covers several different climates. The daily average maximum temperature during the study period was 20.9°C (SD 6.9) and ranged from 16.9°C in Leon to 25.7°C in Seville (Supplemental Material, Table S1). The coldest provinces in Spain registered minimum values below 0°C (e.g., Albacete, Huesca, Teruel, Soria, and Lleida). This finding reflects the importance of cold in some areas of Spain.

The relationship between ambient temperature and risk of occupational injury is summarized by the pooled overall cumulative curve shown in Figure 3a. The curve for Spain had a U-shape, indicating that the risk of occupational injury increases in both cold and hot temperatures. The increases were not restricted to extreme temperatures but were observed across the entire range of temperatures that deviate from the temperature percentile with minimum injuries (27th percentile). The increase in injury risk was mainly associated with temperatures on the same and preceding day (lag 0 and 1), and to a lesser extent with temperatures during the following two and three days (Figure 3b and 3c). The corresponding graphs for each province are shown in the Supplemental Material Figure S1. Differences among provinces were observed. For instance, although a large group of regions presented higher cold effects than heat effects (e.g., Madrid, Toledo, Albacete), in only a few regions were the effects of heat on injuries higher than the effects of cold (e.g., Cadiz, Badajoz). Moreover, some provinces did not have increased injuries with cold (e.g., Almeria, Granada, Jaen, Valencia, Murcia).

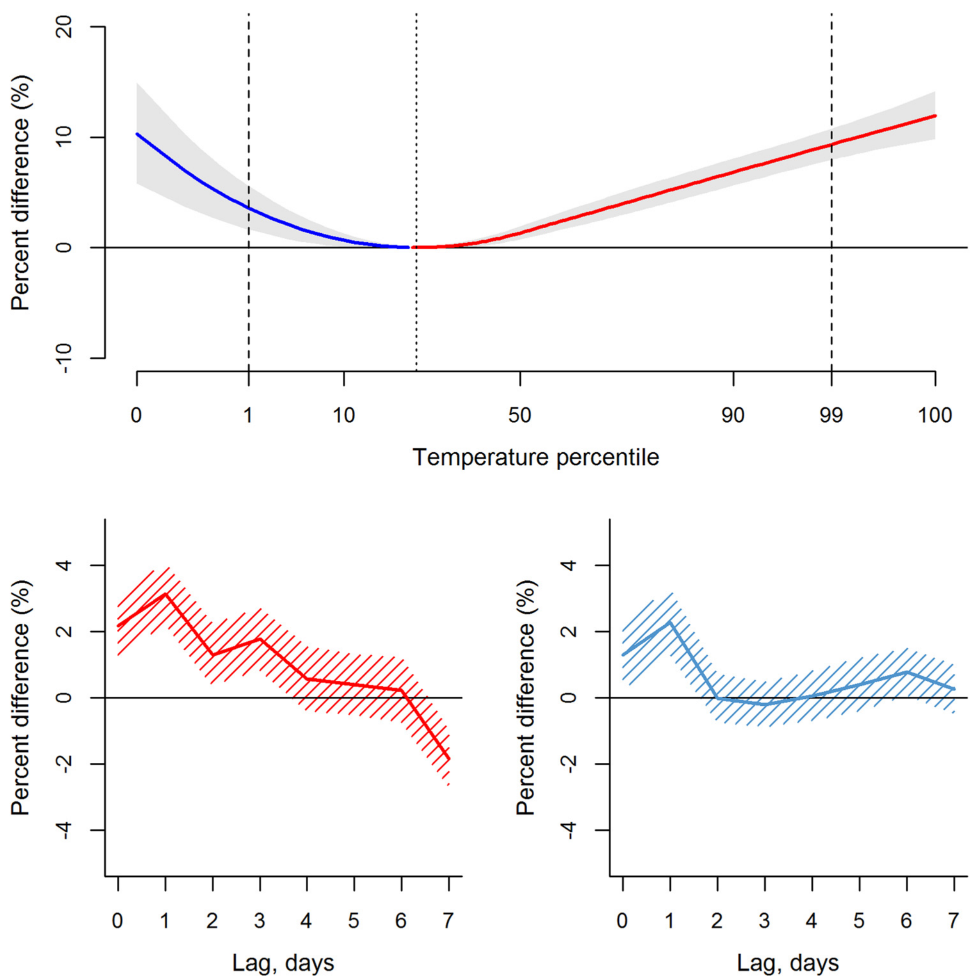

Figure 3. Overall cumulative exposure-response relationship in Spain and lag specific effects. Figure 3a: Exposure-response association in percent difference [with 95% confidence interval (CI) – shaded area] between ambient temperature and occupational injuries in 50 Spanish provinces, 1994–2013. The relationship considers 4 days of lag. The solid line represents the temperature percentile of minimum occupational injuries and dashed lines are temperature in the 1st and 99th percentiles. Figures 3b and 3c: Lag-response relationship between temperature and occupational injuries for cold effects (days with temperatures in the 1st percentile) and heat effects (days with temperatures in the 99th percentile), respectively. Shaded areas represent 95% confidence intervals (CI).

Table 1. Measures of attributable occupational injuries and days of leave (95% CI), and economic losses computed as overall and separately for cold and heat in Spain.

Outcome	Overall	Cold	Heat
Occupational injuries			
Percentage (%)	2.72 (2.44–2.97)	0.32 (0.24–0.38)	2.40 (2.09–2.68)
Moderate	—	0.21 (0.16–0.27)	2.24 (1.95–2.52)
Extreme	—	0.11 (0.09–0.12)	0.17 (0.16–0.18)
Number 1994–2013	434,561 (390,003–475,539)	50,932 (38,983–61,268)	383,629 (333,883–428,334)
Number per year	21,728 (19,500–23,777)	2,547 (1,949–3,063)	19,181 (16,694–21,417)
Number per day	60 (53–65)	7 (5–8)	53(46–59)
Days of sick leave (million)			
Number 1994–2013	13.32 (11.99–14.51)	1.79 (1.35–2.17)	11.53 (9.99–12.88)
Number per year	0.67 (0.60–0.73)	0.09 (0.07–0.11)	0.58 (0.50–0.64)
Days per 1,000 workers per year	42 (38–46)	6 (4–7)	36 (31–41)

Note: —, no information was collected at that particular examination point.

Table 1 shows the number and percentage of occupational injuries attributable to cold and heat, and the attributable number of lost workdays. Overall, more than half a million of the injuries that occurred during the 20-y study period were attributable to nonoptimal temperatures (mean, 60 injuries/day). This number accounts for 2.72% of all occupational injuries, most of which are attributable to moderate heat and cold. Overall in Spain, 13.32 million person-days of work were lost through sick leave related to temperature, representing an annual loss of 42 workdays per 1,000 workers (Table 1). This overall loss was much greater than the observed number of sick-leave days due to internal injuries (681,298), multiple injuries (489,119), or burns and frostbite (242,340).

The distribution of the attributable occupational injuries fraction by Spanish provinces is represented in Figure 4. A different geographical pattern was observed. The provinces where cold had higher influence on occupational injuries were located in the northwest and center of Spain (Figure 4a). In contrast, the highest heat-fraction was observed among regions in the South and east of Spain (Figure 4b). This pattern is similar to the spatial distribution of maximum temperatures in summer and winter (Supplemental Material, Figure S3).

In terms of the economic burden, we estimated that this loss of working days had an annual cost of more than €360 million in Spain, representing 0.03% of GDP in 2015 (Table 2). The highest costs were associated with pain and suffering (corresponding to the level of disability), followed by costs associated with maintaining production, long-term lost income, and health costs. Moderate heat contributed the most to the economic losses.

We also assessed the risk associated with extreme temperatures, specifically the first (extreme cold) and 99th (extreme heat) percentiles of temperature, and found that, in comparison with the temperature percentile of minimum injuries (27^{th}), extreme cold and heat increased the risk of occupational injuries by 4% [95% confidence interval (CI): 2–6] and 9% (95% CI: 8–11), respectively (Figure 5 and Supplemental Material Table S4).

When stratifying the analyses in two time periods, the increased risk of injuries with cold and hot temperatures was still observed in both periods (Supplemental Material, Figure S2 and Table S6). Although the risk of injury during extreme cold was higher in the second period, no differences for heat were observed.

Stratifying these risks by workers' characteristics, we found that, whereas both men and women had elevated risks associated with extreme cold and heat, in general women had higher risk of injuries with cold and men with heat. In terms of age, we observed that older workers had higher injury risk on cold days and younger workers on hot days (Figure 5). We observed no remarkable differences in risk according to nationality and type of contract, although the risk of injury increased in extreme temperatures in both cases.

The economic sectors with a substantial percentage of outdoor workers, namely agriculture, construction, and extractive industries, showed the highest risk of injury associated with extreme temperatures (Figure 6 and Supplemental Material, Table S4). Agricultural workers showed the lowest risk of injury during periods with the coldest temperatures. In addition, the strongest significant associations during cold days were observed for the transport and storage sector, hotel industry, and manufacturing sector. Our results found that nonmanual workers were at higher risk of injury associated with extreme cold.

Apart from hotel industry, all the economic sectors analyzed were male-dominated sectors, with a high percentage of male workers

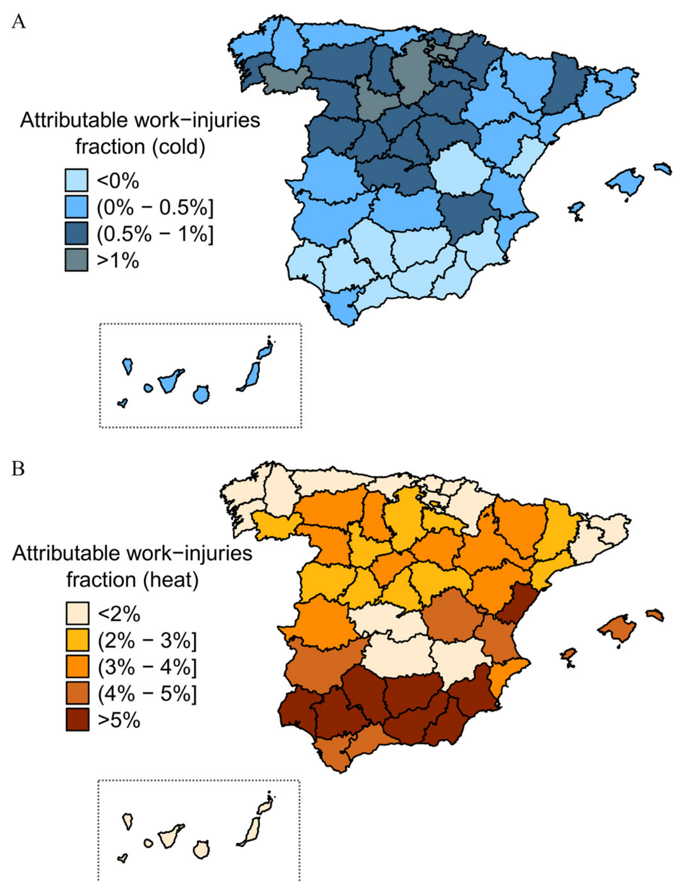

Figure 4. Attributable work-injuries fraction (95% CI) computed as separate components for cold (4a) and heat (4b) by Spanish provinces, 1994–2013. The figure shows the attributable work-injuries fraction for cold (4a) and heat (4b) in each Spanish province. The attributable fraction corresponds to the ratio between the attributable and total number of occupational injuries. The map of Spain and the province borders were downloaded from https://gadm.org, which allows using the data for academic publishing. The final maps were created with the sp library from the R software (version 3.3.3; R Development Core Team).

Table 2. Economic losses due to working at extreme temperatures computed as total and as separate components for cold and heat in Spain.

Cost	Total	COLD			HEAT		
		Extreme	Moderate	Total	Moderate	Extreme	Total
Cost/working day (€)	551						
TOTAL annual costs of extreme temperatures (million €)	366.84	17.17	32.71	49.89	297.82	21.57	319.39
Costs associated with maintaining production[a]	68.01	3.18	6.06	9.25	55.21	4.00	59.21
Long term lost incomes[b]	56.46	2.64	5.03	7.68	45.84	3.32	49.16
Health costs[c]	32.23	1.51	2.87	4.38	26.17	1.89	28.06
Costs of pain and suffering[d]	210.15	9.84	18.74	28.58	170.61	12.35	182.97

Note: Expressed in Euros in 2015. Extreme cold and heat were defined as temperatures below the 2.5th and above the 97.5th percentiles, respectively.
[a]Extra costs of maintaining the same level of production while the worker is on sick leave (overtime payments, substitution and training costs, extraordinary payments to Social Security…).
[b]Total income lost when the worker does not return to work after an occupational injury.
[c]Real costs of treatment and rehabilitation of workers who have suffered an occupational injury in order to recover their health status and help them to return to work.
[d]Costs of pain and suffering associated with the level of disability.

(Supplemental Material Table S5). In the sectors in which we had enough numbers to stratify by sex, we observed that among workers in agriculture, similar effects of heat were observed for both men and women, whereas the protective effect under cold temperatures was observed only in men. In addition, no differences according to sex were seen among workers in hotel industry (Supplemental Material Table S5).

The sector of work and age group were also correlated (Supplemental Material Table S5). No age differences in the effects of temperature on injuries were found among workers in

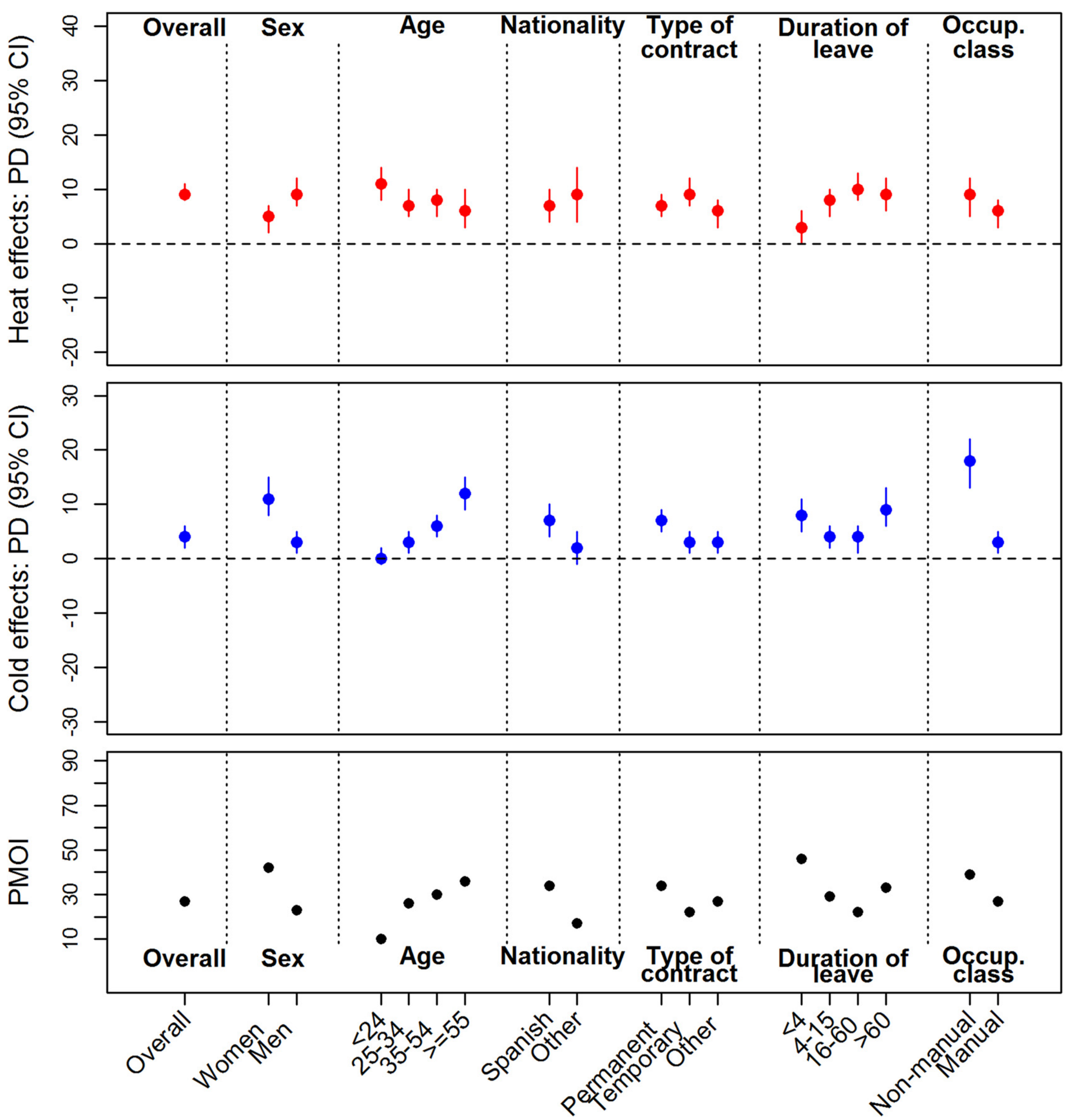

Figure 5. Percent difference (PD) [95% confidence interval (CI)] for the relationship between extreme cold–heat ambient temperatures and occupational injuries in Spain, 1994–2013. Cold effects refer to temperatures in the 1st percentile of maximum temperature versus the percentile of minimum occupational injuries (PMOI). Heat effects refer to temperatures in the 99th percentile versus the PMOI.

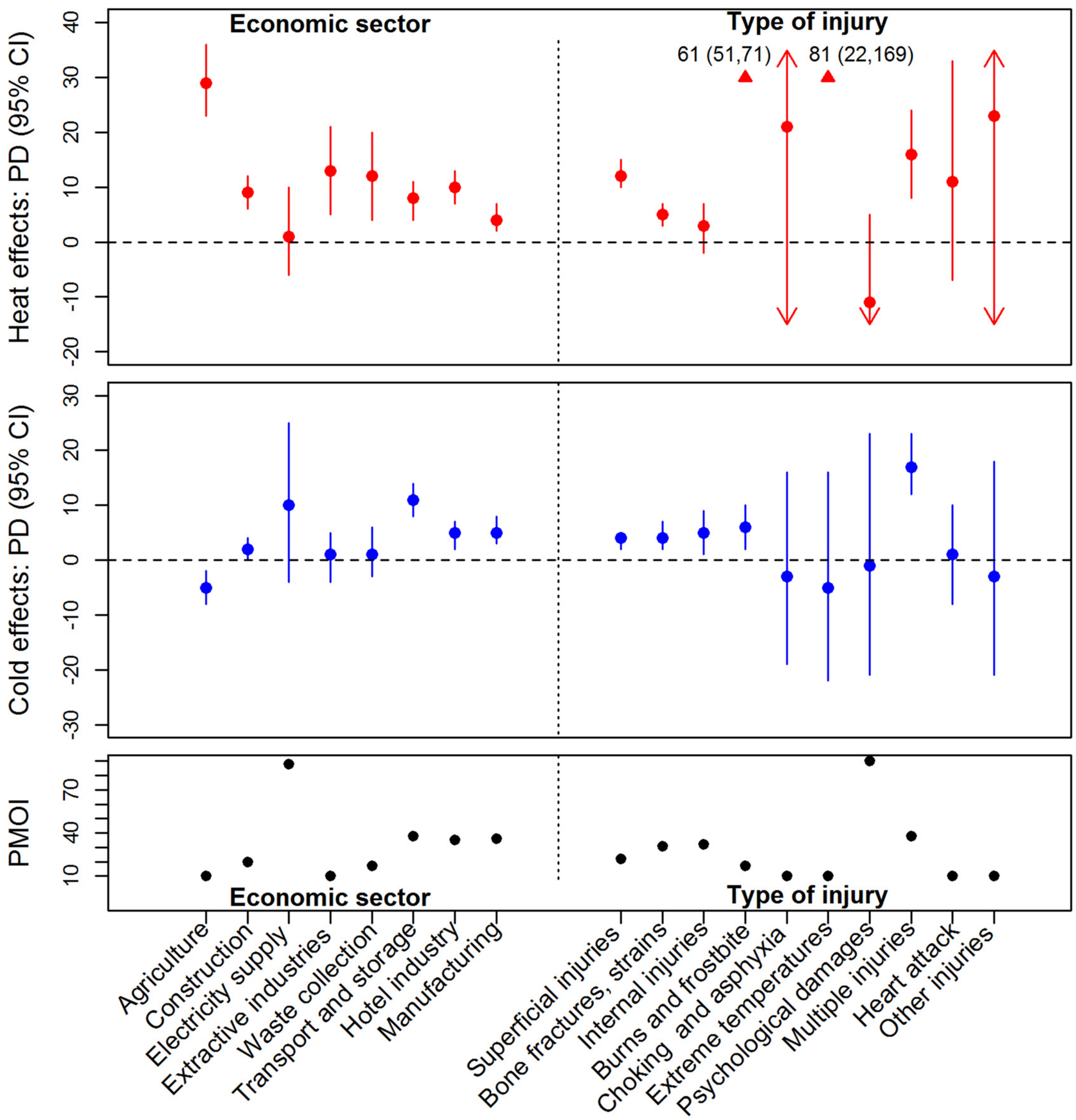

Figure 6. Percent difference (PD) [95% confidence interval (CI)] for the relationship between extreme cold-heat ambient temperatures and occupational injuries in Spain, 1994–2013. Cold effects refer to temperatures in the 1st percentile of maximum temperature versus the percentile of minimum occupational injuries (PMOI). Heat effects refer to temperatures in the 99th percentile versus the PMOI. Confidence intervals ending with an arrow (heat effects) indicate large intervals that are truncated in the figure.

the agriculture sector. On the contrary, in construction, transport, hotel industry, and manufacturing sectors, younger workers presented lower risk of injury with extreme cold, but they had higher risk with extreme hot, in comparison with older workers.

Injuries classified as "effects of extreme temperature" and "burns and frostbite" showed the strongest associations with extreme heat (Figure 6 and Supplemental Material, Table S4). Although this association is expected, given that these injuries have a temperature component in their definition, these two classes of injuries were not driving the overall results. Rather, the risk of superficial injuries and bone fractures, which accounted for 91% of all injuries, was significantly higher during both extreme heat and cold. Other injury types that were also significantly associated with cold include multiple injuries, internal injuries and contusions, and burns and frostbite. Regarding duration of leave, short sick leave (<4 days) increased more strongly in association with extreme cold than with extreme heat.

Results were consistent and sensitivity analyses suggested that our results did not change depending on modeling assumptions (Supplemental Material, Table S3).

Discussion

To our knowledge, this study reports for the first time the association between ambient temperature and occupational injuries at a countrywide level and quantifies its economic costs. Our results indicate that ambient temperature could have a significant effect on occupational injuries. An increase of the risk of suffering an injury was observed during both cold and hot weather. In our study, more than one-half million occupational injuries could be attributable to nonoptimal temperatures. This attributable number of injuries corresponds to an estimated 13 million person-days of work lost in Spain due to temperature, or an annual average of 42 d per 1,000 workers. The estimated annual economic burden is €370 million or 0.03% of Spain's GDP (€2,015).

Our study, including around 16 million occupational injuries, has a much larger sample size than samples in previous studies. Most previous research that has analyzed the effects of heat have shown an association with injuries in the workplace, although the results differed between studies (Bonafede et al. 2016). Although some prior studies observed a linear relationship in the hot temperature range with some differences in intensity (Morabito et al. 2006; Adam-Poupart et al. 2015), others identified thresholds in which the risk of injury started to decrease after reaching extreme temperatures, possibly due to activation of preventive plans (Xiang et al. 2014b). Similar findings to those for heat have been found for cold, although the evidence is more limited, and the results are inconclusive (Morabito et al. 2014; Fortune et al. 2014; Bell et al. 2000).

We found that temperature could be responsible of 2.72% of all occupational injuries that occurred in Spain in the study period. Comparing this finding with the percentage of injuries registered due to other factors, we observed that the effects of exposure were greater in number than burn and frostbite injuries (1.6%), multiple injuries (1.47%), or injuries with psychological damage (0.12%) (Supplemental Material, Table S4).

Most of the occupational injuries due to temperatures were attributable to moderate heat and cold. This finding highlights the importance that public health polices and plans should also cover the ranges of moderate heat and cold, which are more common than extreme temperatures and thus account for a higher number of injuries, despite the smaller relative increase in risk in this range. This pattern has also been reported by studies linking temperature and mortality (Gasparrini et al. 2015b).

Geographical Differences

A difference in the temperature-related injury shape was observed among regions in Spain. Whereas provinces in the south (the hotter regions) showed no cold effects on occupational injuries, others presented higher risk in working at extreme cold and extreme heat. These differences might be due to a variation in climate but also to other factors, such as differences in work activity (occupational sectors) or in the occupational health prevention actions.

The Biological Mechanisms of Working at Extreme Temperatures

The biological mechanisms linking the exposure to extreme ambient temperatures and the risk of occupational injury remain unclear. Most injuries included in this study were bone fractures and superficial injuries, suggesting that the underlying mechanism may be related to decreased concentration or impaired judgment compromising occupational safety (Kjellstrom et al. 2016). Although cognition is already known to be affected by concurrent temperature exposure (Schulte and Chun 2009), the lag pattern observed in this study indicates that the effect of temperature on occupational injuries is not limited to the day of exposure, consistent with the results of other studies (Adam-Poupart et al. 2015). Although our data cannot provide insights on the mechanisms underlying the delayed impact of temperature, possible mechanisms include cumulative fatigue and dehydration.

The Economic Burden of Temperature Related Occupational Injuries

We estimated that extreme temperatures in Spain have an annual cost of around €370 million. Although our economic analysis relied on several assumptions, e.g., the cost calculation was based on an economic analysis conducted only in the region of Catalonia (Abiuso and Serra 2008), our study provides, for the first time, a first-order approximation of the economic costs of injuries attributable to temperature. To date, only one study has estimated the costs associated with temperature, namely an Australian study of 306 injury-compensation claims explicitly classified as heat illnesses (Xiang et al. 2015). Note that the sizeable costs associated with injuries should be added to those attributed to climate variables by other studies, mainly costs associated with reduced productivity and to absenteeism and subsidies (Zander et al. 2015; Hübler et al. 2008; Kjellstrom et al. 2016; Zhao et al. 2016). Specifically, lost productivity is estimated to account for 10% of GDP in some hot regions of the world (Kjellstrom et al. 2016), and for 0.03% of GDP in Germany (Hübler et al. 2008). In China, the cost of high-temperature subsidies was estimated to account for 0.2% of GDP (Zhao et al. 2016).

Differences in Workers' Vulnerability

We found some differences in the estimated risk of occupational injuries according to workers' characteristics. Women appeared to be more vulnerable to cold, and men appeared to be more vulnerable to heat. Most of the economic sectors analyzed were dominated by males, but gender-related differences by sector did not seem to explain apparent differences in susceptibility to temperature between women and men, which could be due thermal biological differences by sex (Karjalainen 2012). Results from some studies reporting that women have lower sweat rates than men in hot climates (Mehnert et al. 2002) could explain the differences found in our study.

The age trend suggested that the workers most vulnerable to heat were the youngest, possibly because these workers tend to do more physically demanding work in hot weather (Bonafede et al. 2016). However, we found a reverse pattern for cold temperatures, which requires further research. Our results differ from those studies assessing other health effects of ambient temperatures. Although the majority of temperature-related mortality and morbidity evidence pointed at the elderly (those older than 65 y) as the most vulnerable (Basu 2009), our study highlighted the effects of temperatures on the working population, which is younger and presumably healthier. In the case of heat, the workers who were younger than 24 appeared to be the most vulnerable group. Thus, our results suggest that young adults are also susceptible to the effects of extreme temperatures.

The sectors with a high percentage of outdoor workers, mainly agriculture and construction, had the highest risk of injury. These workers usually undertake intensive physical activity, even when ambient temperatures are extreme (Xiang et al. 2014a). These sectors have also been found by previous studies to have a high risk of injury during hot periods (Xiang et al. 2015; Morabito et al. 2014; Xiang et al. 2014b). Note that the ambient temperatures analyzed in our study reflect the real conditions of outdoor workers but may not correlate well with the temperatures experienced by indoor workers. In addition, agriculture workers had a temperature percentile with minimum injuries at the coldest temperatures, which may be due to different job characteristics (typology, intensity, severity, and heavy workload) during winter and summer. An explanation for the differences observed in the economic sectors might be due to different workers' socioeconomic status. Some studies have found higher risk of heat-related mortality and morbidity among lower socioeconomic status groups (Benmarhnia et al. 2015).

Unexpectedly, the highest risk of injury associated with extreme cold was observed among nonmanual workers. As one potential explanation, a previous study found that foremen and office workers in the construction industry may be outdoors at work sites and also exposed to extreme temperatures, sometimes with less protective clothing than that of manual workers (Burström et al. 2013).

Limitations

This study has several limitations. First, our results are based on an official register of formal workers and, therefore, informal workers were not included. This omission likely underestimates the effects of extreme temperatures on occupational injuries, as informal workers may have less-regulated and more-adverse work conditions, tend to be employed in low-skilled jobs and to have long work shifts, and are therefore expected to be more at risk (Culp et al.

2011). Second, maximum temperature was used as exposure variable, and we did not consider other parameters, such as humidity. Although several indexes can provide better measures of thermal sensation, some studies have found little differences when using different temperature indexes in the context of temperature-related mortality (Barnett et al. 2010). Importantly, we relied on ambient temperatures, which adequately reflect exposure for outdoors workers but likely do not do so for indoor workers. Third, temperature data were available from a single monitoring station in each province (located in the province's capital). However, daily variations in maximum temperature within a province were quite homogeneous. In a subanalysis with four of the provinces having data from 14 to 21 monitoring stations each, the within-province correlation between stations ranged from 0.87 to 1 (Supplemental Material, Table S2). Fourth, several changes have occurred during the study period for which we did not control, such as sociodemographic changes, the Spanish economic crisis, or changes in workplace regulations. However, after stratifying the study period in two, according to the implementation of an important public occupational health policy, our results were robust. Fifth, the use of a two-step approach to first fit the curves and then find the minimum could have led to some bias in the calculation of attributable fractions. However, a recent paper used simulations to test the method we used (called argmin2 in the reference) and found that there was virtually no bias in the estimation of the minimum in multicity studies with enough statistical power and a clear U-shape relationship, as in our study (Lee et al. 2017). Thus, we expect low bias in finding the minimum temperature and consequently low bias in attributable fractions.

Implications

Our results suggest that a high number of occupational injuries may be attributed to nonoptimal temperatures, and that these injuries result in an important economic cost. Preventive measures to alleviate this burden could be put in place. On the one hand, temperature-health prevention plans and actions should cover not only extreme temperatures but also moderate heat and cold. On the other hand, specific preventive measures for workers should be incorporated in those plans, e.g., measures to restrict working during the coldest/hottest hours, taking rest breaks, ensuring proper hydration, and wearing appropriate clothes. The identification of vulnerable groups of workers may help to focus those policies to reduce the effects of ambient temperatures on occupational health.

Conclusions

In conclusion, this study highlights the negative effect of exposure to moderate and extreme ambient temperatures on occupational health due to increased risk of occupational injuries. Our results also underscore the potential economic costs of this exposure. We also identified groups of workers who appeared to be more vulnerable to workplace injury during periods of extreme temperatures. Considering the predicted increase in global temperatures due to climate change, this study provides useful information for designing targeted interventions and implementing adaptation plans focused on the most vulnerable jobs and workers.

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All authors contributed extensively to the work presented in this paper. XB, ML, and FGB designed the study. EM and XB collected the data. EM, AG and XB analyzed the data. EM, XB, ML, GAW, AG and FGB interpreted the data. EM and XB wrote the manuscript. EM, XB, ML, GAW, AG, FGB and JS made a critical review of the manuscript. All authors approved the final version of this article to be published.

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