The effects of night-time warming on mortality burden under future climate change scenarios: a modelling study

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Summary
Background
The health impacts of climate warming are usually quantified based on daily average temperatures. However, extra health risks might result from hot nights. We project the future mortality burden due to hot nights.

Methods
We selected the hot night excess (HNE) to represent the intensity of night-time heat, which was calculated as the excess sum of high temperature during night time. We collected historical mortality data in 28 cities from three east Asian countries, from 1981 to 2010. The associations between HNE and mortality in each city were firstly examined using a generalised additive model in combination with a distributed lag non-linear model over lag 0–10 days. We then pooled the cumulative associations using a univariate meta-regression model at the national or regional levels. Historical and future hourly temperature series were projected under two scenarios of greenhouse-gas emissions from 1980–2099, with ten general circulation models. We then projected the attributable fraction of mortality due to HNE under each scenario.

Findings
Our dataset comprised 28 cities across three countries (Japan, South Korea, and China), including 9,185,598 deaths. The time-series analyses showed the HNE was significantly associated with increased mortality risks, the relative mortality risk on days with hot nights could be 50% higher than on days with non-hot nights. Compared with the rise in daily mean temperature (lower than 20%), the frequency of hot nights would increase more than 30% and the intensity of hot night would increase by 50% by 2100s. The attributable fraction of mortality due to hot nights was projected to be 3.68% (95% CI 1.20 to 6.17) under a strict emission control scenario (SSP126). Under a medium emission control scenario (SSP245), the attributable fraction of mortality was projected to increase up to 5.79% (2.07 to 9.52), which is 0.95% (~0.39 to 2.29) more than the attributable fraction of mortality due to daily mean temperature.

Interpretation
Our study provides evidence for significant mortality risks and burden in association with night-time warming across Japan, South Korea, and China. Our findings suggest a growing role of night-time warming in heat-related health effects in a changing climate.

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Introduction
Global climate has already been changed by human activities. As an immediate consequence of global climate change, extreme heat conditions could increase the risks of mortality and morbidity from all causes or specific diseases, such as acute cardiovascular events, kidney disorders, and psychiatric illnesses. Based on well-documented epidemiological findings on daily high temperatures or heatwaves, most studies to date have projected an increase in heat-related disease burden under various climate change scenarios. In addition, diurnal temperature range might decrease, altering the distribution of heat during daytime and night time. Ambient heat during the night might interrupt the normal physiology of sleep. The subsequent health effects of reduced sleep are numerous, such as immune system damage, increased susceptibility to cardiovascular disease, chronic illnesses, systemic inflammation, and psychological and cognitive damage. As the body prepares for sleep, a decrease in core body temperature is an important signal for sleep onset. Heat loss from skin helps lower core body temperature in the evening. By affecting core heat shedding, high ambient temperatures during the night can affect circadian thermoregulation. Some studies suggested that poor sleep was associated with elevated night-time warming. Furthermore, one study suggested a connection between hot nights and mortality in areas in southern Europe. However, evidence on this extra effect from a multicounty perspective is scarce.

Larger increases in daily minimum temperature than maximum temperature have been observed in the past few decades especially for high latitudes areas. In addition, night-time heat exposure could be exacerbated by the urban heat island effect within urban areas. In the future, the intensity of night-time warming is
Research in context

Evidence before this study

Previous projection studies focused on daily (24 h) average temperature which does not consider whether night-time warming has an additional effect when quantifying the impact of future warming on human health. To date, there has been little attention on projecting the impact of hot nights on mortality under different climate change scenarios.

Added value of this study

We used a two-stage analysis to estimate the region-specific associations for hot night excess (HNE) and daily mortality after controlling for the effect of daily mean temperature. We projected the attributable fractions of mortality due to hot nights during the current period (1980–2015) and future period (2016–2100) using an hourly temperature series under two climate change scenarios. Our results suggest that night-time heat has a significant impact on mortality, and this effect was evident in all of the study regions. In our projections the influence of hot nights on mortality substantially increase over time, even under a strict carbon emission control scenario. Moreover, even under medium emission control scenarios, the increase in night-time temperatures would have a greater impact on mortality than changes in daily mean temperature.

Implications of all the available evidence

Our study shows that night-time heat could have a significant and independent role in excess mortality providing new insight into the potential impacts of climate change on human health.

Methods

Historical mortality and temperature data

We analysed data from 28 cities across three East Asian countries (China, Japan, and Korea) over the period 1981 to 2010 (appendix p 2). Overall, the selected cities are characterised by varied climates (from tropical to temperate and from coastal to inland) and socioeconomic conditions (middle-income and high-income countries) across East Asia.

We obtained the daily death records from the local Centers for Disease Control and Prevention in each city in mainland China; the Census and Statistics Department in Hong Kong; the Ministry of Health, Labor, and Welfare in Japan; and the Korea National Statistics Office in Korea. Referring to the International Classification of Diseases (ICD), we extracted deaths from all-natural causes or non-external causes (A00-R99 for 10th ICD and 001–799 for 9th ICD). Because we focused on mortality risk due to daily heat and hot nights, we restricted the study period to the warmest 5 months (from May to September). A summary of descriptive statistics for each city is provided in the appendix (p 16).

Because we were unable to obtain the hourly observational data for all the selected cities, we used hourly air temperature outputs from the ERA5-Land dataset, which is a widely used gridded reanalysis dataset produced by the European Centre for Medium Range Weather Forecasts with a 0.1 degree spatial resolution. As ERA5-Land involves data assimilation techniques, it generates very similar temperature distributions to station observations. Many studies have validated the use of ERA5-Land data in epidemiological researches by comparing the effect estimates with those derived from station-based observations in different locations or cities across the world. In the light of these findings, hourly air temperature series for all 28 cities were extracted by the nearest grid cells in the ERA5-Land dataset to quantify the local exposures to daily mean heat and night-time heat.

Future hourly air temperature data

We selected two climate change scenarios from 2015 to 2100, which was motivated by recently released carbon offsetting or reduction schemes from the three countries. In these schemes, the Korean and Japanese governments pledged to make the bloc carbon-neutral by 2050, and the Chinese Government committed to it by 2060. In addition, more than 60% of governments across the world committed to being carbon-neutral around the middle of this century. Therefore, we have reasons to believe the greenhouse-gas emissions would be controlled in the future. On the basis of this background, the scenarios with an assumption of less carbon emission control were selected. Specifically, we selected the scenario with strict carbon emission reduction, which is an update of the representative...
concentration pathway 2.6 based on shared socioeconomic pathways 1 (SSP126), and the scenario with certain carbon reduction, which is an update of the representative concentration pathway 4.5 based on SSP2 (SSP245). In addition, we also evaluated the SSP585 scenario (with an assumption of less greenhouse-gas emission control) as the worst case, and compared the mortality burden under SSP585 with SSP126 and SSP245 within the same period (2070–2099).

We applied a two-step analytic framework to statistically downscale and interpolate the temperature outputs from ten general circulation models under these scenarios (appendix p 1).

**Hot night intensity**

We applied the hot night excess (HNE) to quantify the intensity of nocturnal thermal stress. According to a previous research, this value was calculated by the excess sum of high temperature during the night, as:

\[
HNE = \sum_{i} (t_i - T_{th}) \times I_{thi} (t_i)
\]  

(1)

Where \(n_i\) are the total night hours of day \(j\), \(t_i\) is the night-time temperature at night \(h\) in day \(j\), \(T_{th}\) is the local temperature threshold, and \(I_{thi}\) is calculated as:

\[
I_{thi} (t_i) = \begin{cases} 
0 & \text{if } t_i < T_{th} \\
1 & \text{if } t_i \geq T_{th} 
\end{cases}
\]  

(2)

As suggested in a previous research, we determined the threshold from daily minimum temperature to quantify the intensity of hot night. Referring to the definition of heatwave, we defined of hot night as the 95th percentile of daily minimum temperatures during the historical period. The local sunset and sunrise hour on different days were derived from the Astral package (version 2.2) in Python platform (version 3.8.10).

**Analyses of association between hot nights and mortality**

We estimated the relationship between HNE and daily mortality in each location from 1981 to 2010 through a widely used two-stage analytical framework. During the first stage we did a time series analysis in the R platform (version 2.650).

In the second-stage analysis, meta-regression models were adopted to pool the relative risks (RRs) at the regional level, including Japan, South Korea, north China, and south China. RRs were calculated as the risks of non-accidental mortality at days with specific HNE compared with non-hot night days. We used multivariate meta-analysis models to pool the lag-response associations. We included a set of predictors in our meta-regression to account for the heterogeneity across locations. The location-specific spline of HNE obtained from the first stage analysis was re-centred according to each city’s non-hot night days (HNE=0) to calculate RR estimates at a given HNE. We then specified the exposure-response curves with boundary knots that corresponded to the averages of maximum HNE in each city. Finally, this second-stage analysis generates exposure-response curves pooled at the regional level.

For a comparison, we also estimated the association between mortality and daily mean temperature using the same analytic framework and model parameters with HNE mutually adjusted using the distributed lag non-linear model. Also, in the second stage, we referred to the minimum mortality temperature as the referent temperature to obtain risk estimates at a given daily mean temperature.

The two-stage analysis was done in the R platform (version 4.0.3) using the Dlnm (version 2.4.7) and Mixmeta (version 1.2.0) packages.

**Quantification of hot-night-related mortality burden**

We quantified the mortality burden due to HNE and non-optimum \(T_{max}\) in each city during the historical and future periods under different climate change scenarios.
For each city, the baseline daily mortality was calculated as the average number of total non-accidental deaths per day in each city and was also used in future scenarios. The numbers of attributable deaths and the attributable fraction of mortality due to hot night and non-optimum daily mean temperature were calculated according to a previously described method.\textsuperscript{41} We obtained the total counts of deaths attributable to HNE and T\textsubscript{mean} by summing the contributions from all the days during the five warmest months in a year and gained the total attributable fractions of mortality by dividing the total number of deaths by the attributable deaths due to T\textsubscript{mean} and HNE. We did the above calculations for each city in every scenario.

To account for both the uncertainty of the exposure-response function and the variability of the temperature outputs from different general circulation models, we generated 1000 samples of the coefficients of exposure-response relationships through Monte Carlo simulations, and then generated this result for each of the ten general circulation models. We then obtained empirical CIs corresponding to the 2.5th and 97.5th percentiles of the distribution of the results across coefficients and ten general circulation models.

Because of the potential influence of future adaptation, we adopted an assumption proposed by a previous study\textsuperscript{5}, in which the hot night threshold was defined using the future 95th percentile of temperature instead of the unchanged threshold identified from baseline temperature distributions.

Sensitivity analyses
We did several sensitivity analyses. First, we controlled for daily 24-h average concentration of particulate matter with an aerodynamic diameter 10 μm or lower (PM\textsubscript{10}) and maximum 8-h average concentration of ozone (O\textsubscript{3}) by adding a cross-basis function with a maximum lag of 3 days in the above two-stage analytic models. This sensitivity analysis was restricted among 14 cities with complete meteorological and air pollution data during the same period. Second, we changed several important parameters in our two-stage models, referring to studies that adopting similar models but with different model settings.\textsuperscript{17,34,36} These model parameters included: degrees of freedom for the time variable (four to six per year), the cross-basis functions for T\textsubscript{mean} and HNE (defining the cross-basis function by a natural spline function instead of natural cubic B spline function) and the knots for the cross-basis functions (three internal knots at equally spaced percentiles instead of two internal knots at the 50th and 90th percentiles). Third, for the future projections, we re-calculated the annual attributable fraction of mortality due to HNE from 2070 to 2100, after controlling for daily maximum temperature (T\textsubscript{max}) instead of T\textsubscript{mean} and using other heat thresholds of hot nights (95.0th and 97.5th percentile of daily minimum temperature).

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The funders of the study had no roles in study design, data collection, data analysis, data interpretation, writing of the paper, or decision to submit the Article to publication.
Results

We collected historical mortality data from 28 cities across four regions (Japan, South Korea, north China, and south China). The dataset included 9185598 deaths from 1981 to 2010. The exposure-response curves for the associations of HNE and T_{mean} with daily total mortality for each country or region are shown in figure 1. The relative risk at the 99th percentile of HNE ranges from 1·3 to 1·5, which means the risks of mortality on days with hot night can be 30% to 50% higher than on days with non-hot nights. We also depicted the lag patterns in mortality risks associated with the extreme HNE and T_{mean}. According to the lag structure (appendix p 3), the effects of HNE occurred within 8 days and effects of T_{mean} occurred within 10 days. Greater risks were observed in areas with lower annual mean temperature such as north China and South Korea, whereas smaller risks were found in regions with higher annual mean temperature such as south China.

In terms of the hot night frequency, the analysis of ten general circulation models from Coupled Model Intercomparison Project Phase 6 ensembles revealed that the historical frequency of hot night was lower than 60% of all warm season nights in the late 20th and early 21st centuries. However, climate models suggested a nearly linear pattern of future warming (figure 2A), and the frequency of hot night events was expected to increase rapidly in the next four decades under both SSP126 and SSP245 scenarios (figure 2B). After the 2050s, under SSP126 scenario with strict carbon emission control, the increase of hot night frequency tended to slow down and turned into a plateau period (figure 2A). There is an overall linear increase of hot night frequency after the medium emission-control pathway (SSP245). On average, until the 2090s, the annual hot night frequency increased up to 67·4% (IQR 58·0–71·7) under SSP126 scenarios and 75·6% (59·6–79·8) under SSP245 scenarios across ten general circulation models. In terms of the average HNE, under SSP245, future warming will bring an approximately two-fold increase in the average HNE, from 20·4°C (16·2–23·7) in the 2010s to 39·7°C (31·8–44·2) in the 2090s. Under SSP126, the average HNE will be stabilised after a period of increase until the 2050s. In the 2090s, the average HNE under SSP126 was projected to be 8·0°C (7·4–8·7) lower than that under SSP245.

Modelled hot nights also show marked regional differences (figure 3, appendix pp 4–7). In terms of the mean temperature changes, north China, with the lowest average temperature, was projected to have the largest warming potential (figure 3A; appendix pp 4–7). A similar pattern was also found in cities within four regions, with obvious warming always occurring in cities with cooler weather.

Overall, the frequencies of hot nights and average HNE were expected to increase more rapidly than the average warming trend. Compared with the increments in mean temperature (lower than 20%), hot night frequency and average HNE were projected to experience substantial increases under future climate change scenarios (averaged more than 30% for hot night frequency and more than 50% for HNE in 2090s relative to 2010s, respectively).
As shown in figure 4, attributable fraction of mortality due to HNE and \( T_{\text{mean}} \) were both expected to experience a significant increase in the future. Attributable fraction of mortality due to increases in HNE will be lower than attributable fractions of mortality due to \( T_{\text{mean}} \) in the near term (2010s and 2020s). However, the growth rate of attributable fractions of mortality related to HNE related attributable fraction of mortality was expected to be larger than attributable fraction of mortality related to \( T_{\text{mean}} \). Especially under SSP245, our projections indicated the increase in attributable fraction of mortality related to HNE was projected to surpass the increase in attributable fraction of mortality related to \( T_{\text{mean}} \), around the middle of this century. Till the 2090s, the attributable fraction of mortality related to HNE will increase to 6·3% (95% CI 2·5 to 10·2), which will be 1·0% (–0·4 to 2·3) more than attributable fraction of mortality related to \( T_{\text{mean}} \). Under SSP126, the attributable fraction of mortality related to HNE is projected to increase nearly six times up to 4·2% (1·7 to 6·6), which would be slightly lower than that related to \( T_{\text{mean}} \).

To test the robustness of this result, we displayed the differences in attributable fraction of mortality due to \( T_{\text{mean}} \) and HNE in the 2090s under each general
circulation models. Figure 5 suggests that the higher attributable fraction of mortality related to HNE than attributable fraction of mortality related to $T_{\text{mean}}$ are consistent for most of the general circulation models under SSP245. In addition, as shown in the appendix (p 14), extreme warming under the worst-case scenario (SSP585) would lead to an even higher attributable fraction of mortality due to HNE by the end of the century (years 2070–99). The annual attributable fraction of mortality would reach up to 8·81% (95% CI 3·78–13·84) due to HNE and 7·22% (4·23–10·20) due to $T_{\text{mean}}$.

Furthermore, we estimated the mortality burden attributable to daily average temperature and hot nights for four regions separately. According to the appendix (p 9), the mortality burden is higher in Japan, South Korea, and north China, but slightly lower in south China. Moreover, in Japan and Korea, the attributable fraction of mortality related to hot nights are higher than attributable fraction related to $T_{\text{mean}}$ even under SSP126, due to the larger increase of HNE. However, in north China, the attributable fraction of mortality related to $T_{\text{mean}}$ are consistently higher than attributable fraction of mortality related to HNE, due to the highest average warming with less HNE changes (figure 3).
In terms of the potential influence of future adaptation, the projected increases of attributable fraction of mortality due to HNE after accounting for the future adaptation were lower than those without this consideration, but the attributable fraction of mortality was still consistently close to 2%, especially under SSP245 (appendix p 11).

In sensitivity analyses, as shown in the appendix (p 18) the pooled cumulative RRs of mortality associated with HNE were not appreciably changed after controlling for PM$_{10}$ and O$_3$ concentrations. The RRs were also not appreciably changed after modifying the degrees of freedom for the time variable, the knots, and the cross-basis functions in the two-stage models (appendix p 19). For the future projections, the annual attributable fractions of mortality related to HNE were not appreciably changed from 2070 to 2100 by adjusting for T$_{min}$ instead of T$_{max}$, or using different heat thresholds (appendix p 12).

Discussion

During the warm period in 28 large cities across East Asia, we estimated significant mortality risk and burden due to HNE, a value that represents night-time heat intensity, after controlling for the effect of daily mean temperature. Using multiple climate change scenarios, we also found that hot night frequency and intensity were expected to rise rapidly, even under a strict greenhouse-gas emissions control scenario. From 2010s to 2090s, average hot night intensity was projected to nearly double, resulting in a nearly six-times increase in disease burden. Moreover, under SSP245, the increase in HNE could lead to a greater impact on mortality than the increases in T$_{max}$. The greater mortality burden of hot nights was projected to occur for a range of scenarios, even under the strict emission control targets under the Paris Agreement. Overall, this study extends previous health risk projections of future climate change based on daily mean temperature, by providing evidence of independent health effects of HNE. Our exposure-response associations between T$_{min}$ and mortality are similar to results from the literature in the same geographical area. To our knowledge, the only similar study on the relationship between hot nights and mortality was done in southern Europe, which found similar exposure-response relationships. For the future changes, the projected mortality burden due to changes of T$_{min}$ was similar to a previous scenario study over the same geographical areas.

For the changes of HNE and T$_{min}$ under future scenarios, our results showed that HNE will increase faster than T$_{min}$. Because HNE is a type of accumulated high temperature, it will increase faster than mean temperature when the average temperature exceeds a certain threshold. As indicated by the results from some Japanese cities, such as Osaka, Tokyo, and Nagoya, a relatively lower warming level will still bring higher hot night frequency and more intensive HNE. The projected night-time warming was higher than was the daytime warming in these locations, which is consistent with a study that found a higher increase of daily minimum temperature than daily maximum temperature in many areas across Japan. According to a previous research, as these Japanese cities are surrounded by the sea, stronger night-time warming or higher decrease in diurnal temperature range in these areas are mainly caused by higher mean cloud coverage. By throwing back sunlight into space during daytime and trapping outgoing longwave radiation at night, higher coverage of clouds tend to increase night-time temperature when the average temperature increases.

We chose a range of scenarios to bracket potential effects of future climate change that are most likely to occur under current policies, including the medium and strict greenhouse-gas emissions control scenarios. However, future warming and resultant disease burden depend on global greenhouse-gas emissions control, so the actual conditions might be different from those we modelled. For instance, a study found that 75·2% of global population will experience more compound extreme hot events (ie, continuous high temperatures throughout days and nights) during the end of this century under the SSP585 scenario (the worst case without mitigation policies), which is relatively 39·7% higher than that under SSP245. In this study, we found that the attributable fraction of mortality due to HNE and T$_{min}$ under SSP585 were highest over three scenarios. This result highlights the role of significantly increased hot-night exposure in determining increases in the future heat-related disease burden, despite the uncertainty in scenario selections.

Recently, there is much evidence of increasing tolerance to ambient heat due to many aspects of potential adaptations, including physiological change, improved health services, and behavioural changes (eg, the use of air conditioning). Accordingly, projections of future heat-related mortality that do not take adaptation into account are very likely to overestimate the health impacts of future hot weather. Many recent studies on the projection of heat-related mortality tried to consider the influence of adaptation in different ways. In our sensitivity analyses, we tried to test the potential impact of adaptation in disease burden estimation of future warming based on an assumption proposed by a previous study. Results showed that the projected increases of HNE-related attributable fractions of mortality were reduced, but were consistently close to 2%. Therefore, night-time warming could still play an important role in heat-related disease burden even after accounting for the potential adaptations. It should be also noted that we only considered a change of the hot night threshold as a possible adaptation assumption. Consistent with most previous projection studies, we are unable to consider the change of mortality RRs for hot night due to the potential influences of future adaptation or interventions from different aspects, such as the higher prevalence of air conditioning and population ageing. Further research is still needed to better understand the
mechanisms of population adaptations and their effects on disease burden projections.

Several policy implications could be derived from our results. First, in assessment of disease burden due to non-optimum temperature, one should consider the extra health impacts of disproportional intra-day temperature variations. A more complete health-risk assessment of future climate change can help policy makers improve resource allocation and set priorities. Second, heat during night time should be taken into account in designing heatwave warning systems, especially for vulnerable populations. Third, our results highlight the importance of the night-time use of air conditioning in reducing heat-related mortality risk and burden, although this could also elevate the cost of air conditioning use, increase the heat in the built environment, and might further aggravate the heat-related problems such as urban heat island effects. Fourth, night-time heat could be more severe for residents in low-income communities if they cannot afford the additional expense of air conditioning and tend to close windows during the night time especially in locations where there is a high crime rate. These factors highlight the importance of future public health policies that can ensure the indoor comfort for lower-income groups and older adults to accelerate the achievement of equity in the future development. Fifth, our results highlight the need of stronger mitigation strategies to reduce future warming and adaptation interventions to protect populations from the impacts of warming we cannot avoid. Some interventions, such as high-intensity implementation of cool and evaporative roofs and urban landscaping, have been shown to decrease mean and extreme heat effectively.47 Nowadays, green roofs have been adopted in some cities across China. Our results might be helpful to promote these interventions in urban planning.

Some limitations of this study should be noted. First, we included only 28 cities from three East Asian countries, and thus extrapolation of our results to the whole East Asian region or other regions should be cautious. Second, the study periods and socioeconomic status varied among these cities. The relatively shorter whole East Asian region might amplify night-time heat exposure.50 Nowadays, green roofs have been adopted in some cities across China. Our results might be helpful to promote these interventions in urban planning. For example, the potential urban land-use expansion after future urbanisation might amplify night-time heat exposure.48 However, general circulation models used in this study cannot capture these influences in projecting future temperatures. Fifth, we only evaluated two most probable and common climate scenarios, and some other climate and socioeconomic scenarios, such as SSP119, SSP460, and SSP370, were not taken into account; consequently, our projections do not capture all possible future scenarios.

In conclusion, this study provides novel evidence for the significant mortality risks and burden in association with night-time warming across three countries in east Asia. We project at least a doubling intensity of hot nights with higher increase in mortality burden due to hot nights, suggesting a growing role of night-time warming in heat-related health effects in a changing climate.

Contributors
CH, RC, and HKa contributed to study conceptualisation. CH, RC, HKa, PK, and YZ contributed to study methods. CH, YZ, and LZ did the formal analysis. RC, HKa, HKi, MH, WL, YH, and SEK contributed to data curation and collection of mortality data. CH, YZ, and LZ contributed to visualisation of all the figures and tables. CH, RC, and HKa contributed to the study draft preparation. CH, RC, HKa, HKi, PK, YZ, MH, WL, YH, SEK, and AS contributed to the study revision preparation. RC and HKa supervised all the data analysis and paper writing. The corresponding authors (RC and HKa) had full access to all the data in the study and had final responsibility for the decision to submit for publication after obtaining approval from all co-authors.

Declaration of interests
We declare no competing interests.

Data sharing
Data were collected under a data sharing agreement and cannot be made publicly available. Researchers can refer to the participants, who are listed as co-authors of this Article, for information on accessing the data for each country. Code sources are available from the corresponding authors upon request.

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