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Two-way effect modifications of air pollution and air temperature on total natural and cardiovascular mortality in eight European urban areas

Kai Chen[a,*], Kathrin Wolf[a], Susanne Breitner[a], Antonio Gasparrini[b], Massimo Stafoggia[c], Evangelia Samoli[d], Zorana Jovanovic Andersen[e], Getahun Bero-Bedada[f], Tom Bellander[f,g], Frauke Hennig[h], Bénédicte Jacquemin[i,j], Juha Pekkanen[k,l], Regina Hampel[a], Josef Cyrys[a], Annette Peters[a], Alexandra Schneider[a], on behalf of the UF&HEALTH Study Group

[a] Institute of Epidemiology, Helmholtz Zentrum München–German Research Center for Environmental Health, Neuherberg, Germany
[b] Department of Social and Environmental Health Research, London School of Hygiene & Tropical Medicine, London, UK
[c] Lazio Region Health Service, Department of Epidemiology, Italy
[d] Department of Hygiene, Epidemiology and Medical Statistics, National and Kapodistrian University of Athens, Athens, Greece
[e] Department of Public Health, Center for Epidemiology and Screening, University of Copenhagen, Copenhagen, Denmark
[f] Institute of Environmental Medicine, Karolinska Institutet, Stockholm, Sweden
[g] Stockholm County Council, Centre for Occupational and Environmental Medicine, Stockholm, Sweden
[h] Institute for Occupational, Social and Environmental Medicine, Center for health and Society, University of Düsseldorf, Düsseldorf, Germany
[i] INSERM-Aging and Chronic Diseases, Epidemiological and Public Health Approaches (VIMA), Villejuif, France
[j] Barcelona Institute for Global Health - Campus MAR (ISGlobal), Barcelona, Spain
[k] Department of Public Health, University of Helsinki, Helsinki, Finland
[l] Environment and Health Unit, National Institute for Health and Welfare (THL), Kuopio, Finland

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ABSTRACT

Background: Although epidemiological studies have reported associations between mortality and both ambient air pollution and air temperature, it remains uncertain whether the mortality effects of air pollution are modified by temperature and vice versa. Moreover, little is known on the interactions between ultrafine particles (diameter ≤ 100 nm, UFP) and temperature.

Objective: We investigated whether the short-term associations of particle number concentration (PNC in the ultrafine range (≤100 nm) or total PNC ≤ 3000 nm, as a proxy for UFP), particulate matter ≤ 2.5 µm ($PM_{2.5}$) and ≤ 10 µm (PM_{10}), and ozone with daily total natural and cardiovascular mortality were modified by air temperature and whether air pollution levels affected the temperature-mortality associations in eight European urban areas during 1999–2013.

Methods: We first analyzed air temperature-stratified associations between air pollution and total natural (nonaccidental) and cardiovascular mortality as well as air pollution-stratified temperature-mortality associations using city-specific over-dispersed Poisson additive models with a distributed lag nonlinear temperature term in each city. All models were adjusted for long-term and seasonal trend, day of the week, influenza epidemics, and population dynamics due to summer vacation and holidays. City-specific effect estimates were then pooled using random-effects meta-analysis.

Results: Pooled associations between air pollutants and total and cardiovascular mortality were overall positive and generally stronger at high relatively compared to low air temperatures. For example, on days with high air temperatures (> 75th percentile), an increase of 10,000 particles/cm^3 in PNC corresponded to a 2.51% (95% CI: 0.39%, 4.67%) increase in cardiovascular mortality, which was significantly higher than that on days with low air temperatures (< 25th percentile) [−0.18% (95% CI: −0.97%, 0.62%)]. On days with high air pollution (> 50th percentile), both heat- and cold-related mortality risks increased.

Conclusion: Our findings showed that high temperature could modify the effects of air pollution on daily mortality and high air pollution might enhance the air temperature effects.

* Corresponding author at: Institute of Epidemiology, Helmholtz Zentrum München, Ingolstädter Landstr. 1, 85764 Neuherberg, Germany.
E-mail address: kai.chen@helmholtz-muenchen.de (K. Chen).

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1. Introduction

Exposure to ambient air pollution has been identified as a leading contributor to the global disease burden which caused 4.5 million deaths in 2015 (Cohen et al., 2017). Meanwhile, a large number of epidemiological studies has shown adverse impacts of exposure to both high and low ambient air temperatures on mortality (Basu and Samet, 2002; Curriero et al., 2002; Guo et al., 2014; Ma et al., 2014). Given the increasing concern regarding the health impacts of climate change, interest has grown recently in estimating the joint effects of air pollution and air temperature on health. However, little is known about the potential interaction between air temperature and air pollution, which is crucial for estimating their joint health effects.

Meteorological conditions affect surface air quality by influencing emissions, atmospheric chemistry, and pollutant transport (Fiore et al., 2015). Especially, ground-level ozone (O_3) is formed by chemical reactions between nitrogen oxides and volatile organic compounds in the presence of sunlight and high temperature (Crutzen, 1974; Sillman, 1999). Thus, air pollution can be influenced by air temperature. In studies assessing air pollution health effects, air temperature is usually controlled for as a confounder rather than a modifier (Chen et al., 2013; Li et al., 2017). The potential effect modification of air pollution on mortality by air temperature has been largely neglected, until recently, in epidemiological studies (Stafoggia et al., 2008). On the other hand, air pollution may amplify people's vulnerability to the adverse effects of temperature (Gordon, 2003) and could act as an effect modifier in the short-term effects of air temperature on mortality (Breitner et al., 2014; Ren et al., 2006). This effect modification of temperature health effects by air pollution may be of great importance to public health benefits because air temperature is expected to continue to rise over the 21st century under all emission scenarios (IPCC, 2013), whereas air pollution can be reduced in a few decades to yield measurable improvements in public health (Breitner et al., 2009; Pope III et al., 2009). Thus, both directions of effect modification, hence the two-way effect modifications, matter for public health under a warming climate and changing air quality.

Although a few studies have examined the modifying effect by air temperature on particulate matter (PM)- and O_3-associated mortality, results are inconsistent regarding: (1) the direction of the interaction: most studies reported stronger PM or O_3 effects on days with high air temperatures (Jhun et al., 2014; Kim et al., 2015; Li et al., 2011; Qian et al., 2008; Ren et al., 2008a; Stafoggia et al., 2008), whereas few also reported stronger air pollution effects on days with low air temperatures (Chen et al., 2013; Cheng and Kan, 2012; Sun et al., 2015); (2) the significance of interaction: among 12 studies of PM effects on daily total nonaccidental mortality, only six found statistically significant interactions, five observed nonsignificant interactions, and one reported significance only in Southern Chinese cities (Li et al., 2017; Meng et al., 2012). In contrast, only a limited number of studies have evaluated the modifying effect of air pollution on air temperature-related mortality (Breitner et al., 2014; Li et al., 2015; Ren et al., 2006). PM was found as a significant effect modifier in the association between temperature and total and cardiovascular mortality in Brisbane, Australia (Ren et al., 2006) and Guangzhou, China (Li et al., 2015), but not in three cities of Bavaria, Germany (Breitner et al., 2014). However, these studies have important limitations in characterizing the complex interaction between air temperature and air pollution: first, their analyses were based on a single city analysis; second, they assumed a linear effect, a single lag, or a moving average lag structure for temperature, therefore simplifying to a great extent the nonlinear and delayed temperature-mortality dependencies (Gasparrini et al., 2015b).

Epidemiological evidence on whether air temperature modifies the effect of ultrafine particles (UFP) and vice versa is lacking, mostly due to the unavailability of routinely collected relevant data. UFP are hypothesized to have a high and independent toxic potential due to their small size (< 100 nm), large active surface area, and their ability to penetrate into the pulmonary alveoli and to translocate in the circulation (Brook et al., 2010; HEI Review Panel on Ultrafine Particles, 2013). Few epidemiological studies have reported a (weak) positive association between short-term UFP exposure and mortality (Atkinson et al., 2010; Breitner et al., 2011; Breitner et al., 2009; Lanzinger et al., 2016; Stafoggia et al., 2017).

In the present study, we aimed to investigate the two-way effect modifications of air pollution (UFP, PM, and O_3) and air temperature on total (nonaccidental) and cardiovascular mortality in eight European urban areas. This study is the result of a collaborative effort among the Ultrafine Particles and Health (UF&HEALTH) Study Group in Europe (Stafoggia et al., 2017). The UF&HEALTH Study aimed to gather available data on UFP measures and mortality over a relatively long time period from cities across Europe to enlarge statistical power to detect weak associations (Samoli et al., 2016).

2. Methods

2.1. Data collection

Daily mortality, air pollution, and air temperature data during 1999–2013 were collected from eight European urban areas: Athens (Greece), Augsburg (Germany), Barcelona (Spain), Copenhagen (Denmark), Helsinki (Finland), Rome (Italy), Ruhr area (three adjacent cities including Essen, Mülheim, and Oberhausen, Germany), and Stockholm (Sweden) (Supplemental Information, Fig. S1). Detailed description of the study areas, including main sources of air pollution, are reported in the Supplemental Information, Text S1.

Daily death counts of urban residents were provided by each participating center of the UF&HEALTH Study Group. Mortality data were classified into the following categories using the International Classification of Diseases, 9th revision (ICD-9) and the International Statistical Classification of Diseases and Related Health Problems, 10th revision (ICD-10): deaths from total natural (ICD-9 1-799 and ICD-10 A00-R99) and cardiovascular (ICD-9 390-459 and ICD-10 I00-I99) causes. Respiratory mortality was not investigated because our previous study did not found associations of UFP and PM with respiratory mortality (Stafoggia et al., 2017). For total natural mortality, daily counts were also stratified by sex and age (0–74 years and 75 and above years). The two age groups (nonelderly vs. elderly) were used for analysis as previous studies suggested that the elderly are more vulnerable to the mortality risks of air pollution and air temperature (Anderson and Bell, 2009; Bell et al., 2005; Hajat et al., 2007; Samoli et al., 2008).

Daily mean particle number concentration (PNC, as a surrogate for UFP (HEI Review Panel on Ultrafine Particles, 2013)) was obtained from independent monitoring campaigns in each city. In all cities, one urban or suburban background PNC monitoring site was used, except for a traffic site in Rome. Due to different monitoring instruments used in different cities, PNC was measured in slightly different size ranges (Supplemental Information, Table S1). For Athens, Copenhagen, and Helsinki, PNC was available in the ultrafine range (≤ 100 nm), in the other cities total PNC (≤ 3000 nm) was used as it is often assumed that particles in the ultrafine range dominated PNC (HEI Review Panel on Ultrafine Particles, 2013). In each city, we further collected daily 24-h average PM with an aerodynamic diameter $\leq 2.5\,\mu m$ ($PM_{2.5}$) and $\leq 10\,\mu m$ (PM_{10}) and daily maximum 8-h average O_3 concentrations from multiple stations of the local air quality monitoring networks. Daily concentrations were averaged from all valid monitoring stations in each city, which had at least 75% of the daily data for the study period. For details with regard to air pollution data collection we refer to the preceding publication (Stafoggia et al., 2017). As in previous studies, daily mean air temperature was used as the metric for temperature (Chen et al., 2016; Gasparrini et al., 2015b). Data on daily mean air temperature were collected from local meteorological services or airport meteorological networks. Relative humidity was not collected