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Effects of ambient temperature on mental and neurological conditions in older adults: A systematic review and *meta*-analysis

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ABSTRACT

Background: Emerging research has suggested a link between ambient temperature and mental and neurological conditions such as depression and dementia. This systematic review aims to summarize the epidemiological evidence on the effects of ambient temperature on mental and neurological conditions in older adults, who may be more vulnerable to temperature-related health effects compared to younger individuals.

Methods: A systematic search was conducted in PubMed, Ovid/Embase, Web of Science, and Ovid/PsycINFO on July 17, 2023, and updated on July 31, 2024. We included epidemiological studies investigating the association between ambient temperature exposures and numerous mental and neurological conditions in populations aged 60 years and older. Exclusions were made for studies on indoor or controlled exposure, suicide, substance abuse, those not published as peer-reviewed journal articles, or those not written in English. The risk of bias of included studies was assessed using a tool developed by the World Health Organization (WHO). Qualitative synthesis was performed on all eligible studies, and random-effects *meta*-analyses were conducted on groups of at least four studies sharing similar study design, exposure metric, and health outcome. The certainty of evidence was assessed using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework modified by the WHO.

Results: From 16,786 screened articles, 76 studies were deemed eligible, primarily from mainland China and North America. There was notable heterogeneity in study variables and methodologies. The most commonly used exposure metrics were daily absolute temperature and heat waves, and time-series and case-crossover analyses were the most frequently employed study designs. Meta-analysis of four studies on the effect of a 1 °C increase in temperature on hospital admissions/visits for mental disorders showed a pooled risk ratio (RR) of 1.014 (95 % Confidence Interval, CI: 1.001, 1.026). Comparing heat wave days to non-heat wave days, pooled effect estimates showed increased risk in hospital admissions/visits (RR: 1.269; 95 % CI: 1.030, 1.564; six studies) and mortality related to mental disorders (RR: 1.266; 95 % CI: 0.956, 1.678; four studies). Despite the limited number of studies on cold exposures, they consistently reported that lower temperatures were associated with an increased risk of various mental and neurological conditions.

Conclusions: This review presents epidemiological evidence of the adverse impacts of ambient temperature exposures, such as high temperatures and heat waves, on mental and neurological conditions among the older adult

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population, with overall moderate certainty. The findings highlight the need for greater attention to the mental and neurological health of older adults in the context of climate change and population aging.
Registration number (PROSPERO ID): CRD42023428137.

1. Introduction

Climate change encompasses both short-term temperature extremes and long-term temperature variability, which are associated with adverse health outcomes. The global mean temperature is on the rise, and extreme temperature events such as heat waves are anticipated to become more common, severe, and longer in the future (IPCC, 2023). In the United States (US), the frequency of heat waves has consistently increased, from an average of two per year in the 1960 s to six per year in the 2020 s. In addition, heat waves in the 2020 s were about one day longer and 0.3 °C hotter compared to those in the 1960 s (U.S. EPA, 2024). Numerous epidemiological studies have consistently shown that exposures to non-optimal ambient temperatures, including heat waves and cold spells, are associated with increased risk of mortality and morbidity from a variety of diseases, including cardiovascular, and respiratory outcomes (Anderson and Bell, 2009; Gasparrini et al., 2015; Phung et al., 2016; Son et al., 2019). However, the association between temperature and mental and neurological conditions remains comparatively understudied.

Mental and neurological conditions represent a significant public health burden substantially affecting individuals' quality of life. According to the 2019 Global Burden of Disease study, approximately 970.1 million people worldwide were affected by mental disorders, and they accounted for 125.3 million disability-adjusted life years (DALYs) globally (GBD 2019 Mental Disorders Collaborators, 2022). Neurological disorders were the leading group cause of DALYs in 2021 (443 million), affecting 3.4 billion individuals (GBD 2021 Nervous System Disorders Collaborators, 2024). Mental disorders, also referred to as mental health conditions, are characterized by a disturbance in an individual's cognition, emotional regulation, or behaviour. Examples of mental disorders include depression, anxiety, bipolar disorders, and schizophrenia (WHO, 2022). Neurological disorders are defined as diseases of the central and peripheral nervous system, such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis (WHO, 2016). Mental disorders and neurological disorders (or nervous system diseases) have been categorized separately in the International Classification of Diseases (ICD) system due to their different diagnostic and treatment approaches. However, there is a lack of distinct clinical boundary between them, and they are often grouped together in practice (White et al., 2012). It has been suggested that disorders of the central nervous system often produce both neurological and psychological effects, with neurological and mental disorders potentially sharing genetic and molecular pathophysiology (Butler and Zeman, 2005; Wingo et al., 2022). For example, in the ICD-10, "dementia in Alzheimer's disease" is classified as a mental disorder (F00), whereas "Alzheimer's disease" is classified under nervous system disease (G30). Additionally, mental symptoms play a significant role in various neurological disorders, including multiple sclerosis and Parkinson's disease (Butler and Zeman, 2005).

Limited but growing epidemiological research suggests a link between temperature and a range of mental and neurological conditions, including depression, bipolar disorder, Alzheimer's disease, and Parkinson's disease (Linares et al., 2016; Nori-Sarma et al., 2022; Zhang et al., 2023a). Previous studies reported that heat exposure can lead to increased oxidative stress or neuroinflammation, potentially causing pathophysiological alterations in the brain (Bongioanni et al., 2021; Lohmus, 2018). Cold exposure may lead to vasoconstriction, reducing cerebral circulation and oxygen supply to the brain (Dolcini et al., 2020). Additionally, non-optimal temperatures may disrupt health-promoting behaviors, such as sleep (Lohmus, 2018).

Concurrent with climate change, the global population is rapidly aging. The number of people aged 60 years and older is expected to double, reaching 2.1 billion by 2050 (WHO, 2020b). Mental and neurological conditions among older adults are often underrecognized, but approximately 14 % of those over 60 years of age experience mental disorders, and 38 % are affected by neurological disorders (Institute for Health Metrics and Evaluation, 2020). Furthermore, older adults may exhibit increased vulnerability to the health effects of ambient temperature or extreme temperature events, compared to younger individuals, due to various factors including diminished mobility, existing health conditions, and social isolation (Hansen et al., 2011; Nunes, 2020). Previous studies have shown that older people are at particularly high risk of mortality and morbidity from extreme temperatures (Astrom et al., 2011; Hajat et al., 2007).

Recent systematic reviews have identified associations between high ambient temperatures and a range of mental health conditions (Li et al., 2023a; Liu et al., 2021; Thompson et al., 2018; Thompson et al., 2023). The most recent search covered studies up to April 2022, and the number of studies included in each review ranged from 35 to 144. A systematic review by Amiri et al. (2021), which included 84 studies from 2000 to 2020, suggested links between elevated temperatures and neurological conditions. Appendix 1 provides the method used to identify these relevant systematic reviews. While previous systematic reviews investigated separately on mental or neurological conditions, the overlap in symptomatology and pathophysiology suggests that a combined approach may better reflect their interrelated nature. Additionally, most of previous systematic reviews focused on heat exposures, and the effect of cold exposures remains underexplored despite their potential significance. Moreover, considering potential differences in vulnerabilities to extreme temperature effects in the older population compared to younger individuals, research focusing on older adults is warranted. Thus, conducting a systematic review that explores a comprehensive range of temperature metrics and considers both mental and neurological conditions specifically in the older population would synthesize existing evidence, address knowledge gaps, and inform environmental health policies in the context of climate change and an aging population.

This systematic review and *meta*-analysis study aims to summarize the epidemiological evidence of the effects of ambient temperature, including both heat and cold exposures, on mental and neurological conditions in older adults. The PECOS (Population, Exposure, Comparator, Outcomes, and Study) question of this study is as follows: Among the older population (P), what is the effect of ambient temperatures (E) compared to relatively lower or higher temperatures (C) on the mortality or morbidity from mental and neurological disorders (O) in human observational studies (S)? The exposure considered includes not only continuous ambient temperatures but also extreme temperature events such as heat waves and cold spells, compared to days without heat waves or cold spells.

2. Methods

This systematic review was conducted and reported based on the Cochrane (Higgins et al., 2019) and Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The protocol has been registered at the International Prospective Register of Systematic Reviews (PROSPERO, registered ID: CRD42023428137).

2.1. Eligibility criteria

The inclusion and exclusion criteria structured by PECOS were employed in this review (Table 1).

(1) Population: The review included studies that involved individuals aged 60 years and older, with no restrictions based on gender, race, or ethnicity. The common age threshold for defining "older adults" is typically 60 or 65 years, and this study chose 60 years as the threshold to be inclusive. Studies encompassing a population of all ages were included, provided they included analyses for older adults as a distinct subgroup.

(2) Exposure: Studies evaluating the effects of short-term (days to weeks) or long-term (months to years) exposure to outdoor ambient temperature were included. Eligible temperature metrics included air temperature, apparent temperature (e.g., heat index), and temperature variabilities (e.g., diurnal temperature). Events of heat waves and cold spells were also included. Studies focusing on body temperature, indoor temperature, or seasonal changes without specific consideration of ambient temperature were excluded. We also excluded studies using questionnaires to measure temperature-related exposure (e.g., asking whether symptoms are triggered by weather changes).

(3) Comparators: We included studies that analyzed temperature effects on either a continuous or categorical scale, with comparators being relatively lower or higher temperatures or periods without heat waves or cold spells. For continuous exposures, comparators could encompass the entire range of exposures (e.g., an incremental increase or decrease in exposure) or a specific temperature point (e.g., comparing the 95th percentile of temperature to the 50th percentile of temperature).

(4) Outcome: The outcomes of interest included a broad spectrum of mental and neurological conditions including but not limited to dementia, depression, anxiety, bipolar disorder, and schizophrenia. Studies examining overall mental disorders or nervous system diseases were also included (e.g., ICD-10 codes F00–F99 or G00-G99). The types of health outcomes included mortality, hospital visits or admissions, self-reported symptoms, or functional impairments. Exclusions were made for studies solely focused on substance abuse, suicide, or self-harm. These outcomes were omitted because they predominantly occur in younger populations (GBD 2019 Diseases and Injuries Collaborators, 2020), and the association between temperature and suicide has been the focus of several prior systematic reviews (Frangione et al., 2022; Heo et al., 2021; Thompson et al., 2023). Brain diseases including stroke and brain tumors were excluded, as these conditions are primarily associated with cardiovascular and oncological causes. We excluded studies that examined outcomes not relevant to our interests (e.g., all-cause mortality or heat-related illness) among those with pre-existing mental or neurological conditions.

(5) Study: For study design, the review was limited to epidemiological observational studies in human population, excluding controlled human exposure studies or animal or in vitro experimental research. Additionally, only peer-reviewed journal articles published in English were included, while non-original research articles including reviews, commentaries, editorials, and conference abstracts were excluded.

Table 1
Inclusion and exclusion criteria based on PECOS framework.

Element	Inclusion criteria	Exclusion criteria
Population	- Age ≥ 60 Any genders, races, or ethnicities	Age < 60
Exposure	- Ambient temperature (including temperature-related metrics such as apparent temperature and temperature variability) Heat wave, cold spell	- Indoor exposure Simulated or controlled exposure Studies only comparing different seasons (e.g., summer vs. winter, or seasonal patterns of outcomes) without considering temperature variations Measured with questionnaires
Comparator	- Relatively high or low ambient temperature (either continuous or categorical) Non-heat wave or non-cold spell days	None
Outcome	- Mental and neurological conditions including dementia, Alzheimer's disease, cognitive decline, depression, anxiety, bipolar disorder, schizophrenia, Parkinson's disease, multiple sclerosis, epilepsy, and migraine Types of health outcome include mortality, hospital visits or admissions, symptom, or function	Studies only examining the following: Disorders mostly begin in childhood such as attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder Drug or alcohol abuse Suicide or self-harm Stroke or brain tumor
Study	- Population-based epidemiological study Observational study Peer-reviewed journal articles published in English	- Experimental studies Non-human subjects studies such as animal studies, studies of toxicology or ecology, etc. Human exposure studies or disease-burden studies without exposure–response relationship analysis Reviews, commentary, editorial, books, conference abstracts, meeting reports, etc.

2.2. Search strategy

A systematic search was conducted in PubMed, Ovid/Embase, Web of Science, and Ovid/PsycINFO. In consultation with a research librarian, the search strategy was devised using a combination of free text and controlled vocabulary terms (MeSH and Emtree) for each category of PECOS: population (e.g., "elderly", "older"), exposure/comparator (e.g., "temperature*", "weather"), outcome (e.g., "mental", "neurologic", "depression", "dementia", "cognitive"), and study design (e.g., "epidemiolog*", "observ*"). Within each category, search terms were linked with the "OR" operator to capture any of the terms, and then the categories were interconnected using the "AND" operator. To accommodate the fact that studies on geriatric disorders such as dementia and Alzheimer's disease might not always specify age-related terms in their abstracts, the population search terms were omitted when searching for these specific disorders. We conducted a pilot test of the sensitivity of the search strategy using benchmark papers, which included studies on older adults or geriatric disorders that were part of two previous systematic reviews (Amiri et al., 2021; Liu et al., 2021). Our search strategy successfully captured all the benchmark papers. The original search of all databases was conducted on July 17, 2023, with no limitations on the publication year, and was updated through July 31, 2024. Full search strategies are presented in Appendix 2.

2.3. Study selection and data extraction

All articles retrieved from the electronic databases were imported into EndNote 20, where duplicates, non-English publications, and non-journal articles were excluded. The remaining unique records were then transferred to Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia. https://www.covidence.org) for further processing. The selection of studies involved a two-step procedure, beginning with an initial screening of titles and abstracts, followed by a full-text review. The title and abstract screening phase engaged sixteen reviewers (GB, YC, DF, RS, YS, HMC, SK, SYK, XN, CC, SH, JYS, KB, HK, NCD, and MLB), and twelve reviewers (GB, YC, DF, RS, YS, HMC, SK, SYK, XN, JYS, KB, and HK) participated in the subsequent full-text examination. During each step, reviewers were paired up and each pair was randomly assigned the same set of articles. The two reviewers in each pair independently assessed these articles to ensure adherence to the eligibility criteria., Any disagreements were resolved by a third reviewer (GB, YC, or MLB). Additional studies not retrieved by the electronic database searches were identified by backward citation chaining of the included studies and relevant review articles using Citation Chaser (Haddaway et al., 2022). The studies identified by citation chaining were checked for duplicates against the records previously screened during the database searches. Any duplicates or records not categorized as journal articles were excluded. The remaining records identified from citation chaining underwent a manual screening process conducted by the two reviewers (GB and YC).

A data extraction form (Appendix 3) was developed to collect the following information from each included study: author, publication year, study location (country and region), study period, study design, characteristics of the study population including age range, sample size, details on exposure assessment, details on outcome assessment, statistical method and confounders adjusted for in analysis, descriptive statistics on exposure, and effect estimates (including type of measure, point estimate, and uncertainty measure such as p-value or confidence interval). All effect estimates for each pair of exposure and outcome studied were extracted. In cases where multiple estimates were provided for a given exposure/outcome pair by different models, the result from the primary model (the most adjusted model or the one most favored by the authors) was selected. When age-specific analyses were conducted, the findings for each age group were separately recorded. Further information on missing or unclear information regarding the age of the study population or effect estimates was requested from the corresponding author of each relevant study. For studies where results were presented graphically without corresponding numerical data, we extracted the effect estimates using WebPlotDigitizer version 5.2 (Rohatgi, 2024). The extraction form was pilot tested and validated using a small number of eligible studies. Ten reviewers (GB, YC, DF, RS, YS, HMC, XN, JYS, KB, and HK) participated in the data extraction process, with each study independently reviewed by two of these individuals. Any discrepancies in data extraction were resolved by a third reviewer (GB or YC).

2.4. Risk of bias assessment

A risk of bias (RoB) assessment tool developed by the World Health Organization (WHO, 2020a) was employed to evaluate all studies included in this review. The tool encompasses six domains: confounding, selection bias, exposure assessment, outcome measurement, missing data, and selective reporting. Each domain is further divided into subdomains, with each subdomain being assessed as having a 'low', 'moderate', or 'high' RoB. If all subdomains within a domain received a low RoB rating, the domain as a whole was classified as low RoB. If at least one subdomain was assessed as having a high RoB, the whole domain was rated as high RoB. In cases where at least one subdomain had a moderate RoB without any subdomain evaluated as high RoB, the whole domain was assigned a moderate RoB.

The WHO guideline provided detailed guidance for evaluating the RoB in each subdomain and making an overall judgment for each domain (WHO, 2020a). The authors adhered to this guidance in their assessments. Within the confounding domain, the subdomain asking "Were all confounders considered and adjusted for in the analysis?" required a determination based on critical and additional potential confounders identified prior to conducting the RoB assessment. Studies examining short-term and long-term exposure to temperature use different study designs and exposure contrasts. Therefore, short-term studies (time series and case-crossover) and long-term studies (cohort and case-control) have different sets of potential confounders. For example, in long-term studies, the year of enrolment could be a potential confounder, as both exposure and outcome might have annual trends. On the other hand, in short-term studies, the day of the week or holidays could be potential confounders, since these studies focus on daily variations in exposure and outcome. The list of potential confounders suggested for air pollution studies in the WHO guideline was adapted to suit temperature studies (Appendix 4). Humidity and other weather variables were added as additional potential confounders due to their close association with temperature. Additionally, the day of the week was categorized as an additional potential confounder rather than a critical one, considering the weaker association between temperature and specific days of the week. Specifically for this subdomain, a study was rated as low RoB if it adjusted for all critical and additional potential confounders that were *a priori* determined. If all critical potential confounders but not all additional potential confounders were adjusted for, the study was assigned a moderate RoB. If a study did not adjust for any critical potential confounders, the study was classified as high RoB.

The overall judgment of RoB at the study level was not made, in accordance with the WHO guideline. The WHO Working Group considered it inappropriate to combine or carry forward the ratings from individual domains into an overall assessment at the study level. RoB assessment was conducted independently by the first author (GB) and one of four other reviewers (YC, DF, RS, or HK). Any disagreements were resolved through discussion between GB and MLB.

2.5. Data synthesis

For evidence synthesis, studies were grouped by exposure metrics: high temperature (continuous measure for high air temperature), heat wave, cold exposure, and others. Within the group of continuous high temperature exposures, studies were further subdivided based on the type of comparator used: those reporting effect estimates for incremental increases in exposure (e.g., per 1 °C increase) and those using percentiles to report effect estimates (e.g., comparing the 97th percentile temperature to the minimum risk temperature). Measures of association were standardized to risk ratios (RRs), except for studies reporting a regression coefficient for a continuous outcome (e.g., cognitive function test score). Odds Ratios and Hazard Ratios were assumed to be equal to RRs, given the generally low incidence of outcomes (Li et al., 2023b; Liu et al., 2021). Percent change (PC) was transformed into RR using the equation: $RR = 1 + (PC/100)$. For studies that provided effect estimates per increment or decrement in exposure (e.g., interquartile increase in mean temperature), these estimates were converted to reflect a change of one unit (e.g., 1 °C) using the equation: $RR\ (\text{per 1 unit}) = [RR\ (\text{per } c \text{ units})]^{1/c}$, where c is the reported increment (or decrement) in units (Song et al., 2021). Estimates based on percentiles, which typically occurred for studies considering non-linear associations, or for categorical exposures (e.g., heat wave versus non-heat wave days) were used as reported in the original studies, without alterations. For studies that provided effect estimates across multiple age subgroups, only estimates relevant to individuals aged 60 years and older were included for the main results in this review. When these older age groups were further divided into sub-categories (e.g., 75–84 and ≥ 85 years), their effect estimates were combined using a fixed-effects model to provide a single effect estimate per study.

For the narrative synthesis, we compared and summarized the direction, magnitude, and precision (95 % CIs) of the associations across studies. We also qualitatively explored sources of heterogeneity by examining differences in study designs, exposure assessment methods, outcomes studied, and statistical approaches. The results of individual studies were visually presented in forest plots. Additionally, for mental disorders, where most studies included all-age groups, we examined whether the effects of temperature differed between younger and older populations. Where applicable, effect estimates for each age sub-group, including those under 60, were displayed without being pooled.

Meta-analyses were conducted when at least four individual studies with comparable study design, exposure metric, and health outcome (including disease category) were available. Estimates per 1 °C change and those based on percentiles were not treated as directly comparable. Among the percentile-based estimates, studies with both the same target and reference temperature percentiles (e.g., 99th percentile vs. 50th percentile) were considered comparable. Estimates for heat waves (or cold spells) were considered comparable even though the specific definitions for heat waves differed among studies. While there are no established guidelines for the minimum number of studies required for a *meta*-analysis, which is often small ($\leq$5) (Davey et al., 2011), this study set four as the minimum number needed to justifiably conduct a *meta*-analysis. When more than two studies were conducted at the same location for the same exposure and outcome, only the most recent study was included in the *meta*-analysis. A random-effect *meta*-analysis with the DerSimonian and Laird (DL) estimator was employed to account for between-study heterogeneity. The degree of statistical heterogeneity of effect estimates between studies was evaluated using the I^2 and τ^2 values, and Cochran's Q chi-square test. For sensitivity analysis, the Restricted Maximum-Likelihood (REML) estimator was applied in place of the DL estimator. Due to the limited number of studies included in each *meta*-analysis, neither subgroup analysis nor *meta*-regression was performed. Statistical tests for publication bias, such as Egger's test for funnel plot asymmetry, were not performed due to the limited number of studies ($n \leq 5$) in each *meta*-analysis. It is generally advised not to use funnel plot asymmetry tests when there are fewer than 10 studies (Sterne et al., 2011). The package 'meta' in the R software 4.3.0 (The R Development Core Team, Vienna, Austria) was used to generate forest plots and perform the *meta*-analyses.

2.6. Certainty of evidence

The certainty of the overall evidence for each exposure metric was assessed using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework modified by the WHO (WHO Global Air Quality Guidelines Working Group on Certainty of Evidence Assessment, 2020). Consistent with the standard GRADE approach (Balshem et al., 2011), the modified version also grades the certainty of the evidence as high, moderate, low, or very low. However, unlike the standard approach which starts the rating at low certainty, the modified version starts at moderate certainty. The certainty of the evidence can then be downgraded or upgraded for each GRADE domain: risk of bias, inconsistency, indirectness, imprecision, and publication bias for downgrading; and large effect, dose–response, and opposing plausible residual bias and confounding for upgrading. Each domain was assigned a score of 0 (no change), −1, −2, (downgrade by one or two levels), or + 1 (upgrade by one level).

3. Results

3.1. Study selection

From the database search, 36,519 records were identified, of which 19,733 were removed before screening due to being duplicates, non-English, or non-journal articles (Fig. 1). This left 16,786 unique articles, with 16,549 subsequently excluded during title and abstract screening. A further 163 were excluded after full-text review, resulting in 74 studies being deemed eligible for inclusion in this review. The major reason for the exclusion of full-text articles was an irrelevant population (e.g., not including individuals aged 60 or older in the study population or not reporting effect estimates for these groups). An additional 2 records identified through citation chaining brought the total to 76 articles included in the review. Due to substantial heterogeneity in study variables or methodologies, *meta*-analyses were only feasible for 12 studies. A minimum of four studies with comparable outcomes, exposure metrics, and study designs was required to conduct a *meta*-analysis, but 61 studies did not meet this requirement. For example, the number of studies focusing on individual disease categories (e.g., depression or Alzheimer's disease), as opposed to overall mental disorders, was insufficient for conducting a *meta*-analysis. Three studies could not be presented in forest plots or included in the *meta*-analysis

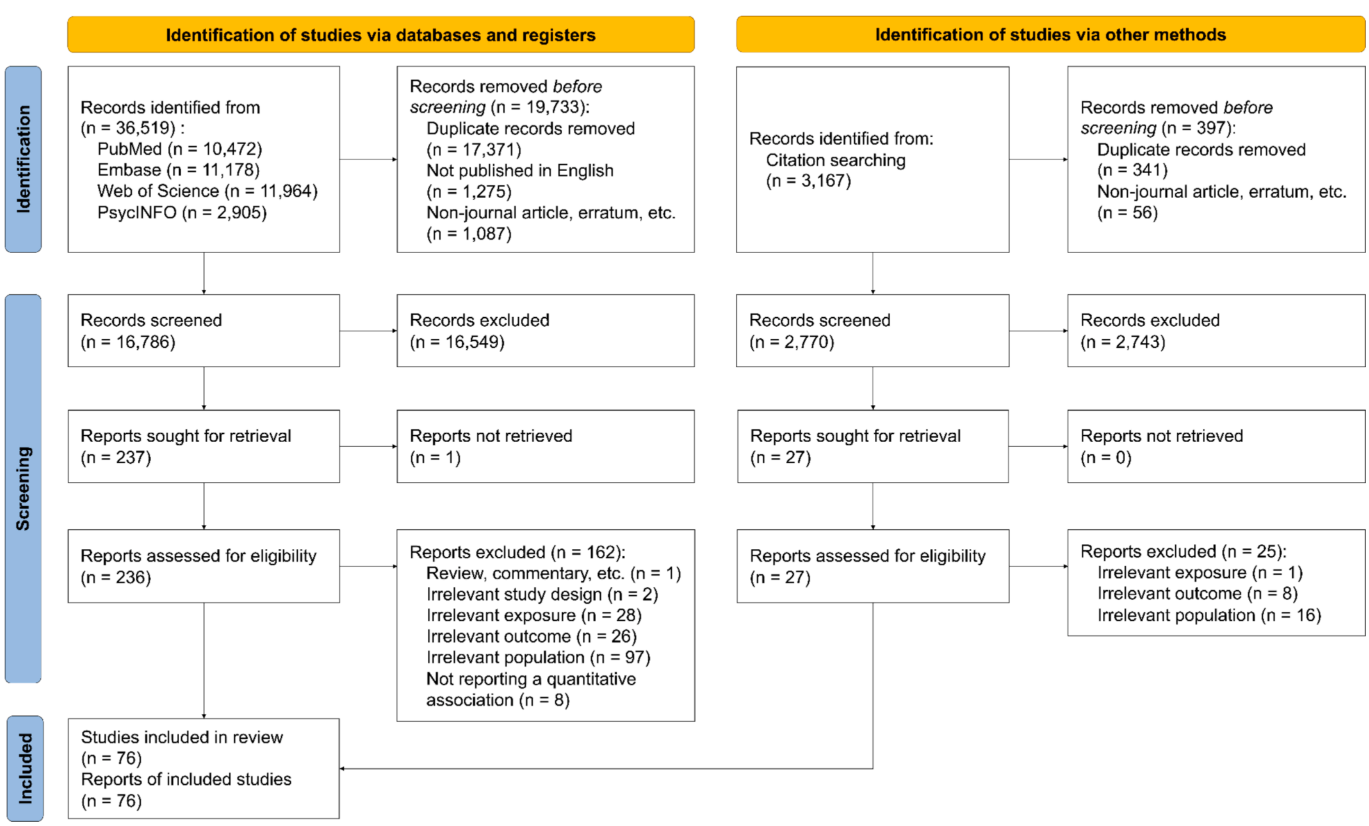

Fig. 1. Flowchart of the selection process for studies included in this review.

because the exact reference temperatures for their effect estimates were not provided (da Silva et al., 2020; da Silva et al., 2022; Vida et al., 2012).

3.2. Study characteristics

Table 2 summarizes the characteristics of the 76 studies included in this review, and more detailed information is available in Appendix 5. Among the 76 studies, 33 were published between 2022 and 2024. The majority of the studies were conducted in mainland China ($n = 30$) and North America (12 in the USA and 2 in Canada). Europe was the location for 11 studies (3 each in Spain and the UK, 2 in Finland, and 1 each in France, Germany, and Switzerland), and 10 were conducted in other Asian countries besides mainland China (4 in Vietnam, 2 each in Japan and Taiwan, and 1 each in South Korea and Hong Kong). There were 6 studies conducted in Australia and 5 in Brazil (a world map can be found in Appendix 6). No study was conducted in multiple countries. Regarding study design, 55 studies employed time-series or case-crossover designs, and 16 utilized cohort designs (including panel studies). There was 1 case-control study and 2 studies that evaluated excess mortality during specific heat waves. The age threshold defining the older population differed across studies, with the majority using 60 years and older, or 65 years and older. The sample sizes provided in Table 2 represent the numbers for the older population, ranging from 489 to 23 million. Some studies that included all-age populations did not report the numbers by age group; the total sample sizes for these studies can be found in Appendix 5. The most commonly employed exposure metric was daily temperature (mean, maximum, or minimum, $n = 44$), mostly obtained from monitoring data, followed by heat waves in 14 studies. Other metrics included cold spells ($n = 4$), apparent temperature (or heat index, $n = 8$), and temperature variability ($n = 3$). Some studies employed less common metrics such as the number of days with extreme temperatures or specific temperature ranges ($n = 3$), and the heat stress index ($n = 2$). Most studies focused on hospital (or emergency department, ED) admissions/visits or mortality ($n = 60$). Mental disorders as a single category were the most frequently investigated outcome ($n = 31$), while nervous system diseases, also treated as a single category, were examined in 9 studies. Sub-categories of diseases investigated included dementia or Alzheimer's disease ($n = 13$), depression or depressive symptoms ($n = 9$), and cognitive function ($n = 11$).

3.3. Risk of bias in studies

The results of the RoB assessment are summarized in Fig. 2, and detailed evaluations with judgements are provided in Appendix 7, a separate Excel spreadsheet. Of the 76 studies reviewed, 17 (22.3 %) studies were rated as moderate RoB in the confounding domain, mainly because the analysis did not adjust for some of the additional potential confounders. In short-term studies, factors such as holidays and days of the week were often not adjusted for; and in long-term studies, individual characteristics such as physical activity and marital status were often not adjusted for. Two long-term studies were rated as high RoB due to the lack of adjustment for socioeconomic status, which was predetermined as a potential critical confounder. In the exposure assessment domain, 11 (14.5 %) studies were classified as moderate RoB for reasons such as unclear exposure assessment methods or failure to consider spatial exposure contrasts in long-term studies. In the domain of missing data, 9 (11.8 %) studies were assessed as moderate RoB, primarily due to the occurrence of missing outcome data being relatively frequent ($\geq$10 %) and potentially differing between disease cases and non-cases. Only a few studies were assessed as moderate RoB in the selection bias, outcome measurement, and selective reporting domains. Among the 12 studies included in the *meta*-analyses, 5 studies were marked as moderate RoB in the confounding domain, but none were considered high RoB across any domains. It should be noted that a high or moderate RoB rating does not necessarily indicate that a study is biased, and it may reflect the lack of comprehensive details in the publication.

3.4. Results of individual studies

Figs. 3 and 4 display forest plots of effect estimates and 95 % confidence intervals (CIs) for different disease categories from studies examining the association between high temperatures and mental and neurological conditions using time-series or case-crossover designs. Fig. 3 illustrates RRs per 1 °C increase in temperature, whereas Fig. 4 presents percentile-based RRs. Most studies suggested an increased risk of various mental and neurological conditions associated with higher ambient temperatures. However, the methodologies for exposure assessment, even within the same exposure metric, varied among the studies, including differences in data source (monitoring vs. modeling) temperature thresholds, the lag period considered, or the application of seasonal restrictions. For instance, Linares et al. (2016), using temperature data from monitoring stations, calculated RR per 1 °C increase above a threshold of 34 °C, considering the lag period of up to 5 days. In contrast, Gong et al. (2022), using modeled temperature data, calculated RR per 1 °C increase above a threshold of 17 °C, specifically during the summer season, with a 7-day lag period. Studies reporting percentile-based RRs explored the non-linear association between temperature and health outcomes, revealing variability in the shape of the exposure–response curves across studies. For example, Nori-Sarma et al. (2022) and Lee et al. (2018a) observed a monotonically increasing risk of ED visits or admissions for mental disorders with increasing temperatures, whereas Yoo et al. (2021a) and Chan et al. (2018) identified a U-shaped curve. The minimum risk temperature, which indicates the temperature at which the risk of health outcomes is lowest, also varied among the studies.

Fig. 5 presents a forest plot on the association between heat waves and mental and neurological conditions, based on time-series or case-crossover designs. Most studies reported a heightened risk of morbidity or mortality from mental and neurological conditions during heat wave days compared to non-heat wave days. However, the studies on heat waves were conducted in a limited number of countries, particularly in Australia. The criteria for defining a heat wave varied across studies, as a universal definition of a heat wave does not exist in science or policy. Generally, a heat wave is defined as several consecutive days of high temperatures exceeding a specific threshold, which could be absolute (e.g., 35 °C) or relative (e.g., the 90th percentile of a community's temperature range). Based on episode analysis rather than time-series or case-crossover designs, Thompson et al. (2022) observed significant excess deaths from dementia and Alzheimer's disease during the 2020 heat waves in England, in comparison to non-heat wave days before and after the period of interest. Using a similar study design, Fouillet et al. (2006) reported excess deaths attributed to the 2003 heat wave in France, with 550 deaths for mental disorders and 781 for nervous system diseases among those aged 75 years and older.

Forest plots for other exposure metrics including cold temperatures, apparent temperature, or temperature variability are included in Appendix 8. Overall, lower temperatures, increase in apparent temperature, or higher temperature variability were consistently associated with increased risk of various mental and neurological conditions. Forest plots categorized by disease types, covering frequently studied diseases (mental disorders, nervous system diseases, dementia, depression, and cognitive function), can be found in Appendix 9. In addition, forest plots showing age-specific effect estimates from studies that conducted age-stratified analyses are provided in Appendix 10. Several studies observed increased effect estimates in older age groups compared to younger ones (Chan et al., 2018; Lee et al., 2018b; Yoo et al., 2021a; Yoo et al., 2021b), whereas other studies found the estimates to be consistent across different age groups.

Table 2
Characteristics of the included studies ($n = 76$).

Author (year)	Study location	Study period	Study design	Age*	Sample size (older adults)	Exposure type	Health outcome	Disease category
Astone and Vaalavuo (2023)	Nationwide, Finland	1998–2017	Time-series	All (≥ 65)	Not reported	Temperature	Mortality; Hospital visit	Mental disorders (dementia and Alzheimer's disease)
Basu et al. (2018)	Nationwide, USA	2005–2013	Time-series	All (≥ 65)	28,592	Apparent temperature	Hospital visit	Mental disorders
Bobb et al. (2014)	Nationwide, USA	1999–2010	Time-series	≥ 65	23.7 million	Heat wave	Hospital admission	Nervous system disease
Bundo et al. (2021)	Bern, Switzerland	1973–2017	Case-crossover	All (≥ 65)	13,596	Temperature	Hospital admission	Mental disorders
Chan et al. (2018)	Hong Kong, China	2002–2011	Time-series	All (≥ 60)	23,452	Temperature	Hospital admission	Mental disorders
Chen et al. (2019)	Nationwide, Taiwan	2003–2013	Cohort	All (≥ 65)	86,731	Temperature	Hospital visit; Hospital admission	Depression
Chen et al. (2021)	Guangzhou, China	2010–2018	Time-series	All (≥ 65)	Not reported	Cold spell	Mortality	Mental disorders; nervous system disease
Chen et al. (2023)	Nationwide, China	2011–2015	Cohort	≥ 45 (≥ 60)	19,992	Hot/cold days	Self-reported symptom	Depression
Cohen et al. (2024)	New York, USA	1995–2014	Case-crossover	All (≥ 65)	642,489	Diurnal temperature range	Hospital visit	Anxiety, mood, adjustment, and schizophrenia disorders
Corvetto et al. (2023)	Curitiba, Brazil	2017–2021	Time-series	All (≥ 65)	6,955	Mean temperature	Hospital visit	Mental disorders
Corvetto et al. (2024)	Curitiba, Brazil	2017–2021	Time-series	All (≥ 65)	34,278	Mean temperature	Hospital visit	Mental disorders
Crank et al. (2023)	Arizona, USA	2006–2014	Time-series	All (≥ 65)	5,258	Minimum temperature	Hospital admission	Schizophrenia
Culqui et al. (2017)	Madrid, Spain	2001–2009	Time-series	≥ 60**	3,287	Temperature	Hospital admission	Alzheimer's disease
da Silva et al. (2020)	Curitiba, Brazil	2010–2016	Time-series	All (≥ 60)	Not reported	Temperature	Hospital admission	Mental disorders
da Silva et al. (2022)	Parana state, Brazil	1996–2015	Time-series	≥ 40 (≥ 60)	Not reported	Minimum temperature	Hospital admission	Mental disorders
Dai et al. (2016)	Greater Boston area, USA	2000–2008	Cohort	All (≥ 70)	594	Temperature	Function/ performance	Cognitive function
Dang et al. (2022)	Ho Chi Minh City, Vietnam	2017–2019	Time-series	All (≥ 61)	7,780	Temperature; heat wave	Hospital admission	Mental disorders
Deng et al. (2022)	New York State, USA	2017–2018	Case-crossover	All (≥ 65)	Not reported	Temperature; heat index	Hospital visit	Mental disorders
Fouillet et al. (2006)	Nationwide, France	2003	Episode analysis	All (≥ 75)	Not reported	Heat wave	Mortality	Mental disorders; nervous system disease
Gao et al. (2024)	Nationwide, China	2013–2019	Case-crossover	All (≥ 65)	124,331	Hot night excess and hot day excess	Mortality	Dementia
Gasparrini et al. (2012)	England and Wales, UK	1993–2006	Time-series	All (≥ 65)	1,870,655	Temperature	Mortality	Mental disorders (dementia, schizophrenia); nervous system disease (Parkinson's disease, neurodegenerative diseases)
Gong et al. (2022)	9 Government regions, England	1998–2009	Time-series	≥ 16 (≥ 75)	Not reported	Temperature	Hospital admission	Dementia
Hansen et al. (2008)	Adelaide metropolitan area, Australia	1993–2006	Time-series	≥ 15 (≥ 75)	Not reported	Heat wave	Mortality; Hospital admission	Mental disorders; Alzheimer's disease
Ho et al. (2020)	Hong Kong, China	2007–2014	Case-control	≥ 65	5,438	Hot/cold days	Mortality	Dementia
Hou and Xu (2023)	Nationwide, China	2008–2018	Spatiotemporal series	≥ 65	17,791	Temperature	Function/ performance	Cognitive function
Hua et al. (2023)	25 provinces, China	2010, 2014	Cohort	All (≥ 60)	Not reported	Hot/cold days	Self-reported symptom	Depression
Jiang et al. (2022)	20 cities, China	2017–2018	Cohort	≥ 40 (≥ 65)	1,851	Temperature	Self-reported symptom	Depression
Jin et al. (2023)	28 provinces, China	2011–2018	Cohort	≥ 45 (≥ 65)	Not reported	Apparent temperature	Self-reported symptom	Depression
Kollanus et al. (2021)	Nationwide, Finland	2000–2014	Time-series	All (≥ 65)	170,525	Heat wave	Mortality	Mental disorders; nervous system disease
S. Lee et al. (2018)	6 major cities, South Korea	2003–2013	Time-series	All (≥ 65)	51,085	Temperature	Hospital admission	Mental disorders
M. Lee et al. (2018)	Nationwide, Japan	2013	Cohort	All (≥ 65)	1,067	Temperature	Self-reported symptom	Anxiety, depression

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Table 2 (*continued*)

Author (year)	Study location	Study period	Study design	Age*	Sample size (older adults)	Exposure type	Health outcome	Disease category
Li et al. (2022)	3 cities, China	2013–2018	Case-crossover	All (≥ 65)	Not reported	Cold spell	Hospital visit	Anxiety
Lin et al. (2023)	10 prefectures, Japan	2010–2019	Case-crossover	All (≥ 85)	121,402	Temperature	Mortality	Nervous system diseases (major neurodegenerative diseases, Alzheimer's disease, and Parkinson's disease)
Linares et al. (2016)	Madrid, Spain	2001–2009	Time-series	≥ 75**	986 deaths; 6,725 admissions	Temperature	Mortality; Hospital admission	Parkinson's disease
Linares et al. (2017)	Madrid, Spain	2001–2009	Time-series	≥ 60**	1,175	Temperature	Hospital admission	Dementia
Liu et al. (2024)	Jiangsu province, China	2015–2020	Case-crossover	All (≥ 85)	30,942	Heat wave/cold spell	Mortality	Dementia
Lo et al. (2021)	Nationwide, Taiwan	1996–2007	Cohort	≥ 65	5,780	Temperature	Function/ performance	Cognitive function
Min et al. (2019)	Yancheng city, China	2014–2017	Time-series	All (≥ 60)	489	Apparent temperature	Hospital admission	Mental disorders
Nitschke et al. (2007)	Adelaide, Australia	1993–2006	Time-series	All (≥ 65)	Not reported	Heat wave	Mortality; Hospital admission	Mental disorders; nervous system disease
Nitschke et al. (2011)	Adelaide, Australia	1993–2008	Case-crossover	All (≥ 65)	Not reported	Heat wave	Hospital visit; Hospital admission	Mental disorders; nervous system disease
Niu et al. (2020)	Beijing, China	2016–2018	Time-series	All (> 65)	2,118	Apparent temperature	Hospital visit	Mental disorders
Niu et al. (2024)	Beijing, China	2016–2018	Time-series	All (> 65)	2,118	Mean temperature	Hospital visit	Mental disorders
Nori-Sarma et al. (2022)	Contiguous US	2010–2019	Case-crossover	≥ 18 (≥ 65)	601,229	Temperature	Hospital visit	Mental disorders
Qiu et al. (2021)	25 provinces, China	2016	Cohort	≥ 60	3,448	Temperature	Function/ performance	Cognitive function
Qiu et al. (2022a)	Contiguous US	2000–2016	Case-crossover	≥ 65	458,492	Temperature	Hospital admission	Depression, schizophrenia, bipolar disorder
Qiu et al. (2022b)	25 provinces, China	2012, 2016	Cohort	≥ 60	2,623	Temperature	Function/ performance	Cognitive function
Su et al. (2021)	5 cities, China	2014–2017	Time-series	All (≥ 75)	Not reported	Temperature	Mortality	Nervous system disease
Sun et al. (2022)	Hefei, China	2015–2020	Time-series	All (≥ 60)	1,981	Apparent temperature	Hospital visit	Epilepsy
Thompson et al. (2022)	Nationwide, England	2020	Episode analysis	All (≥ 65)	102,102	Heat wave	Mortality	Dementia and Alzheimer's disease, Parkinson's disease
Tran et al. (2024)	Six provinces, Vietnam	2005–2020	Time-series	All (> 60)	Not reported	Mean temperature	Hospital admission	Mental disorders
Trang et al. (2016a)	Hanoi, Vietnam	2008–2012	Time-series	All (≥ 60)	1,595	Heat wave	Hospital admission	Mental disorders
Trang et al. (2016b)	Hanoi, Vietnam	2008–2012	Time-series	≥ 61	1,766	Temperature	Hospital admission	Mental disorders
Vida et al. (2012)	Québec, Canada	1995–2007	Time-series	≥ 15 (≥ 65)	38,509	Temperature	Hospital visit	Mental disorders
Wang et al. (2012)	Brisbane, Australia	1996–2005	Case-crossover	All (≥ 65)	Not reported	Heat wave	Mortality; Hospital admission	Mental disorders
Wang et al. (2014)	Toronto, Canada	2002–2010	Time-series	All (≥ 60)	Not reported	Temperature	Hospital admission	Mental disorders
Wang et al. (2018)	Hefei, China	2005–2014	Time-series	All (≥ 61)	737	Temperature	Hospital admission	Schizophrenia
Wei et al. (2019)	New England, USA	2001–2011	Cohort	≥ 65	3,069,816	Temperature; temperature variability	Hospital admission	Dementia
Williams et al. (2012)	Adelaide, Australia	1993–2009	Time-series	All (≥ 65)	Not reported	Temperature	Hospital visit	Mental disorders
Xu et al. (2019)	Brisbane, Australia	2005–2013	Case-crossover	≥ 65	302 deaths, 846 admissions	Heat wave	Mortality; Hospital admission	Alzheimer's disease
Ye et al. (2024)	Nationwide, China	2011, 2015	Difference in Difference	All (> 65)	Not reported	Heat wave/cold spell	Function/ performance	Cognitive function
Yi et al. (2019a)	Hefei, China	2005–2014	Time-series	All (≥ 61)	1,570	Apparent temperature	Hospital admission	Schizophrenia
Yi et al. (2019b)	Hefei, China	2005——2014	Time-series	All (≥ 61)	1,570	Temperature variability	Hospital admission	Schizophrenia

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Table 2 (*continued*)

Author (year)	Study location	Study period	Study design	Age*	Sample size (older adults)	Exposure type	Health outcome	Disease category
Yi et al. (2021)	Nationwide, China	2013, 2015	Cohort	All (≥ 60)	2,865	Heat stress degree days index	Function/ performance	Cognitive function
Yin et al. (2023)	Nationwide, China	2013–2019	Case-crossover	All (≥ 65)	402,974	Mean temperature	Mortality	Neurodegenerative diseases
Yoo et al. (2021a)	New York, USA	2009–2015	Time-series	All (≥ 65)	188,097	Temperature	Hospital visit	Mental disorders
Yoo et al. (2021b)	New York, USA	2009–2016	Time-series	All (≥ 65)	8,379	Temperature	Hospital visit	Mental disorders
Zeng et al. (2010)	22 provinces, China	2002, 2005	Cohort	≥ 65	15,973	Temperature	Function/ performance	Cognitive function
Zhang et al. (2020)	3 cities, China	2013–2018	Case-crossover	All (≥ 64)	101,627	Temperature	Hospital visit	Mental disorders (depression, organic mental disorders, anxiety, schizophrenia)
Zhang et al. (2023a)	5 states, US	2005–2016	Case-crossover	≥ 45 (≥65)	3,320,879	Temperature	Hospital visit	Alzheimer's disease, Alzheimer's disease-related dementias
Zhang et al. (2023b)	Nationwide, Brazil	2000–2015	Case-crossover	All (≥ 60)	Not reported	Temperature	Hospital admission	Epilepsy
Zhang et al. (2024)	Nationwide, China	2010–2018	Cohort	All (≥ 60)	Not reported	Mean temperature	Function/ performance	Cognitive function
Zhao et al. (2016)	Hefei, China	2005–2014	Time-series	All (≥ 65)	860	Temperature variability	Hospital admission	Schizophrenia
Zhao et al. (2021b)	Münsterland, Germany	2007–2010	Cohort	≥ 68	777	Temperature	Function/ performance	Cognitive function
Zhou et al. (2023a)	Chongqing, China	2014–2019	Time-series	All (≥ 60)	28,461	Humidex	Hospital visit	Depression
Zhou et al. (2023b)	Nationwide, China	2008–2018	Cohort	All (≥ 80)	6,051	Heat wave	Function/ performance	Cognitive function
Zhou et al. (2024)	Liuzhou, China	2013–2020	Time-series	All (> 60)	739	Mean temperature	Hospital admission	Schizophrenia

*Age restriction applied to the entire study population in each study, with the age range in parentheses indicating the subgroup of older adults.
**The age demographic of the study population was not clearly specified; hence the actual age range of the study population might be imprecise.

3.5. Meta-analysis

The *meta*-analysis of five studies examining the effect of a 1 °C increase in temperature on hospital admissions/visits for mental disorders resulted in a pooled RR of 1.014 (95 % CI: 1.001, 1.026) (Fig. 6). The results remained consistent when employing the REML method instead of the DL method, with a pooled RR of 1.015 (95 % CI: 0.999, 1.031). Results of the *meta*-analysis on the association between heat waves and hospital admissions/visits and mortality for mental disorders are provided in Fig. 7. The pooled effect estimates suggested an increase in both hospital admissions/visits (RR: 1.269; 95 % CI: 1.030, 1.564) and mortality (RR: 1.266; 95 % CI: 0.956, 1.678) during heat wave days compared to non-heat wave days. Applying the REML method led to minor changes in results (RR: 1.359; 95 % CI: 0.964, 1.916 for hospital admissions/visits, and RR: 1.285; 95 % CI: 0.921, 1.792 for mortality).

3.6. Certainty of evidence

Table 3 presents the evaluations and judgments on the certainty of evidence. The overall certainty of evidence for each exposure metric was evaluated by considering all reviewed studies. In the RoB domain, no downgrading was applied as most studies were deemed to have low or moderate RoB in the evaluated domains. No downgrading was applied in the inconsistency domain as well, since the variation in effect estimates across studies was more likely attributable to substantial methodological heterogeneity, study locations, or population characteristics rather than to uncertainties in effect sizes. There was no downgrading in the indirectness domain, since all studies made direct comparisons relevant to the PECOS framework, and the imprecision domain was not downgraded because the majority of studies had sufficiently large sample sizes to provide reliable confidence intervals. Downgrading was not applied for publication bias due to the small number of studies involved in the *meta*-analysis. An upgrade was applied in the dose–response domain for studies on high temperatures, which consistently showed an increased risk of health outcomes with higher temperatures. However, no upgrade was applied to other exposure metrics. Consequently, the evidence quality of the studies reviewed was considered high for high-temperature exposure and moderate for other exposure metrics.

4. Discussion

4.1. Key findings

This systematic review provides synthesized epidemiological evidence regarding the effects of different ambient temperature exposures, including high or low daily temperature, heat waves, cold spells, and temperature variability, on various mental and neurological conditions among an older adult population. The majority of the studies reviewed reported the adverse effects of non-optimum temperature exposures, including heat and cold, on hospital admissions/visits or mortality related to mental and neurological conditions. Despite the inclusion of only a limited number of studies in the *meta*-analyses, the pooled effect estimates indicated significant associations of higher temperature and heat waves with increased hospital admissions/visits or mortality due to mental disorders.

4.2. State of knowledge

Previous systematic reviews, which did not impose age restrictions, showed associations between high ambient temperature and mental health outcomes including mood disorders, organic mental disorders, and schizophrenia (Li et al., 2023a; Liu et al., 2021; Thompson et al., 2018; Thompson et al., 2023). Meta-analyses by Liu et al. (2021) showed a significant association between a 1 °C increase in temperature and a 3.1 % increase in mental disorder-related mortality (RR: 1.031; 95 % CI: 1.011, 1.052, $n = 5$), as well as a 0.7 % increase in morbidity (RR: 1.007; 95 % CI: 1.005, 1.009, $n = 12$). Meta-analyses by Li et al. (2023a) found

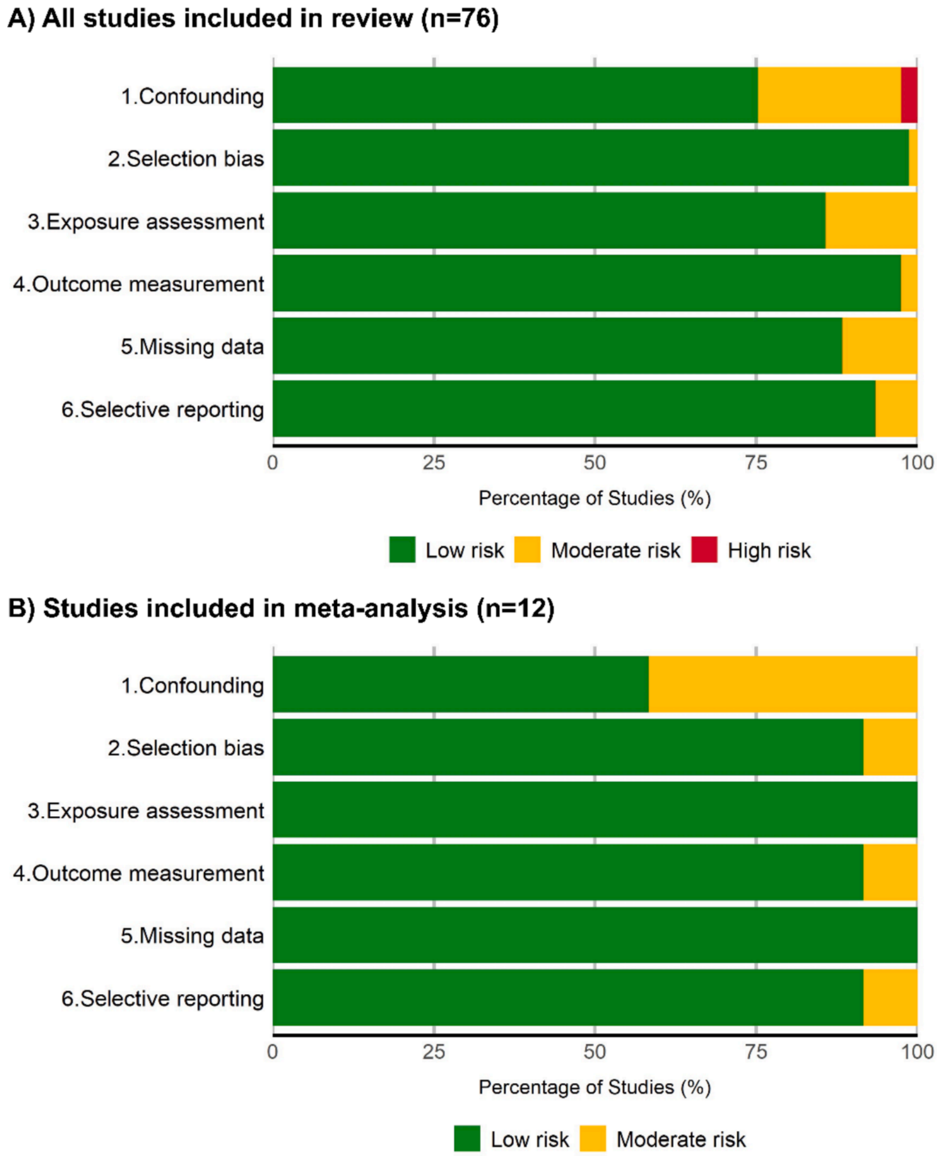

Fig. 2. Summary of the risk of bias assessment across A) all studies included in the systematic review and B) studies included in the *meta*-analysis.

that heat waves (RR: 1.05; 95 % CI: 1.02, 1.08, $n = 7$) and extremely high temperatures (99th percentile temperature vs. MRT, RR: 1.18, 95 % CI: 1.08, 1.29, $n = 8$) were associated with an increased risk of morbidity from mental disorders. A systematic review by Amiri et al. (2021) suggested the association between high temperature and neurological conditions including Alzheimer's disease, epilepsy, and stroke, although no quantitative synthesis was provided. The present study has identified 45 recent studies that were not included in these earlier reviews, incorporating both mental and neurological conditions. The findings from this study are consistent with previous reviews, and further strengthen the evidence of temperature effects, particularly on neurodegenerative outcomes such as dementia and cognitive function.

To the best of our knowledge, there has been no systematic review study specifically addressing the impact of temperature on mental and neurological conditions in the older population. A subgroup *meta*-analysis by Liu et al. (2021) showed that the effect estimates for a 1 °C increase in temperature on mental disorders were higher in people aged 65 years and older (mortality RR: 1.025, 95 % CI: 1.015, 1.035, $n = 6$; morbidity RR: 1.010, 95 % CI: 1.005, 1.015, $n = 5$) compared to those younger than 65 (mortality RR: 1.017, 95 % CI: 1.005, 1.028, $n = 6$; morbidity RR: 1.005, 95 % CI: 1.003, 1.006, $n = 9$). The study by Liu et al. (2021), however, focused on heat exposures, not incorporating cold exposure or temperature variabilities, included only time-series or case-crossover studies, and did not examine neurological conditions such as dementia. While the present study did not conduct a subgroup analysis by age, we examined studies on mental disorders that compared age-specific estimates; however, the findings were inconsistent (Figure S9). Although older individuals are often identified as vulnerable to the health effects of heat or cold, particularly regarding cardiovascular and respiratory outcomes (Åström et al., 2011; Gronlund et al., 2014), the evidence related to mental and neurological conditions is relatively limited. Older adults may face greater challenges in coping with extreme temperatures compared to younger populations due to diminished thermoregulation and the presence of comorbidities. Cognitive decline can also impair an older individual's ability to recognize and respond appropriately to temperature changes, potentially delaying necessary protective actions. Social isolation and decreased mobility, which are often more prevalent among older adults, may further increase their susceptibility to the mental health impacts of temperature exposures (Hansen et al., 2011; Petrova and Khvostikova, 2021).

Our findings are consistent with those from several previous

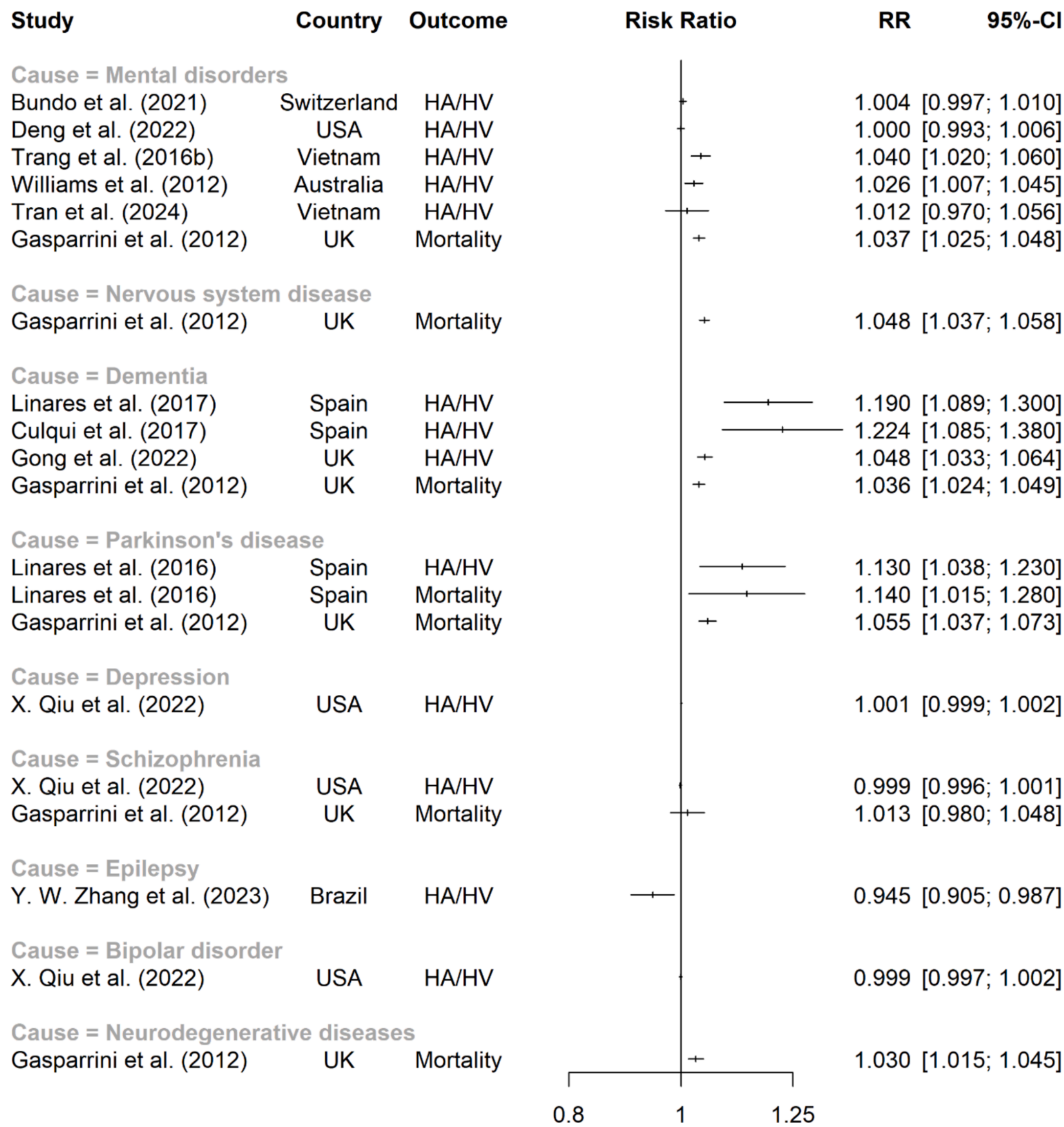

Fig. 3. Forest plot of the risk ratios for different mental and neurological conditions associated with a 1 °C increase in temperature. *Note: Effect estimates may be measured above a certain temperature threshold, which varies across studies. HA/HV = hospital admissions or hospital visits.*

systematic reviews that focused on specific neurodegenerative outcomes, such as cognitive function, dementia, and Parkinson's Disease. Zhao et al. (2021a) reported a positive association between higher temperatures and an increased risk of cognitive impairment and dementia, though the *meta*-analysis, which included three observational studies, was not statistically significant. Systematic reviews of experimental studies where temperature exposures were directly manipulated indicated that exposure to heat or cold air could lead to a decline in cognitive performance (Falla et al., 2021; Martin et al., 2019; Yeganeh et al., 2018). Bougea et al. (2023) suggested a potential link between temperature exposure and the progression of Parkinson's disease, though they noted the evidence base was limited. In this review, the focus on specific disease categories revealed a limited number of studies with diverse methodologies, which made conducting a *meta*-analysis impractical. However, 9 out of 10 studies investigating dementia or Alzheimer's disease reported statistically significant associations with high temperature or heat waves (Figure S6), and 4 out of 5 cohort studies on cognitive function observed a significant decline associated with high temperatures (Figure S8).

4.3. Potential biological mechanisms and explanations

While the underlying mechanisms are not fully understood, there is biological plausibility for the association between ambient temperature and mental and neurological conditions. Heat exposure can lead to alterations in central neurophysiological signaling and activate neurodegenerative processes through mechanisms such as oxidative stress, excitotoxicity, and neuroinflammation (Bongioanni et al., 2021; Lohmus, 2018). Animal studies found that elevated temperatures increase metabolic demands and can disrupt the blood–brain barrier, leading to an accumulation of reactive oxygen species and oxidative damage to neural tissue (Chauhan et al., 2021; Yan et al., 2023). Additionally, evidence from both human and animal studies suggested heat exposure may disrupt neurotransmitter balance, affecting mood regulation and potentially leading to conditions such as anxiety and depression (Roelands and Meeusen, 2010). Sleep disturbances are also common during heat exposure due to discomfort and altered circadian rhythms, which can further impact mental health (Obradovich et al., 2017). Cold exposure, on the other hand, can cause vasoconstriction and reduce cerebral blood flow, leading to hypoxia and potential neuronal injury in humans (Alba et al., 2019; Castellani et al., 2002). An observational

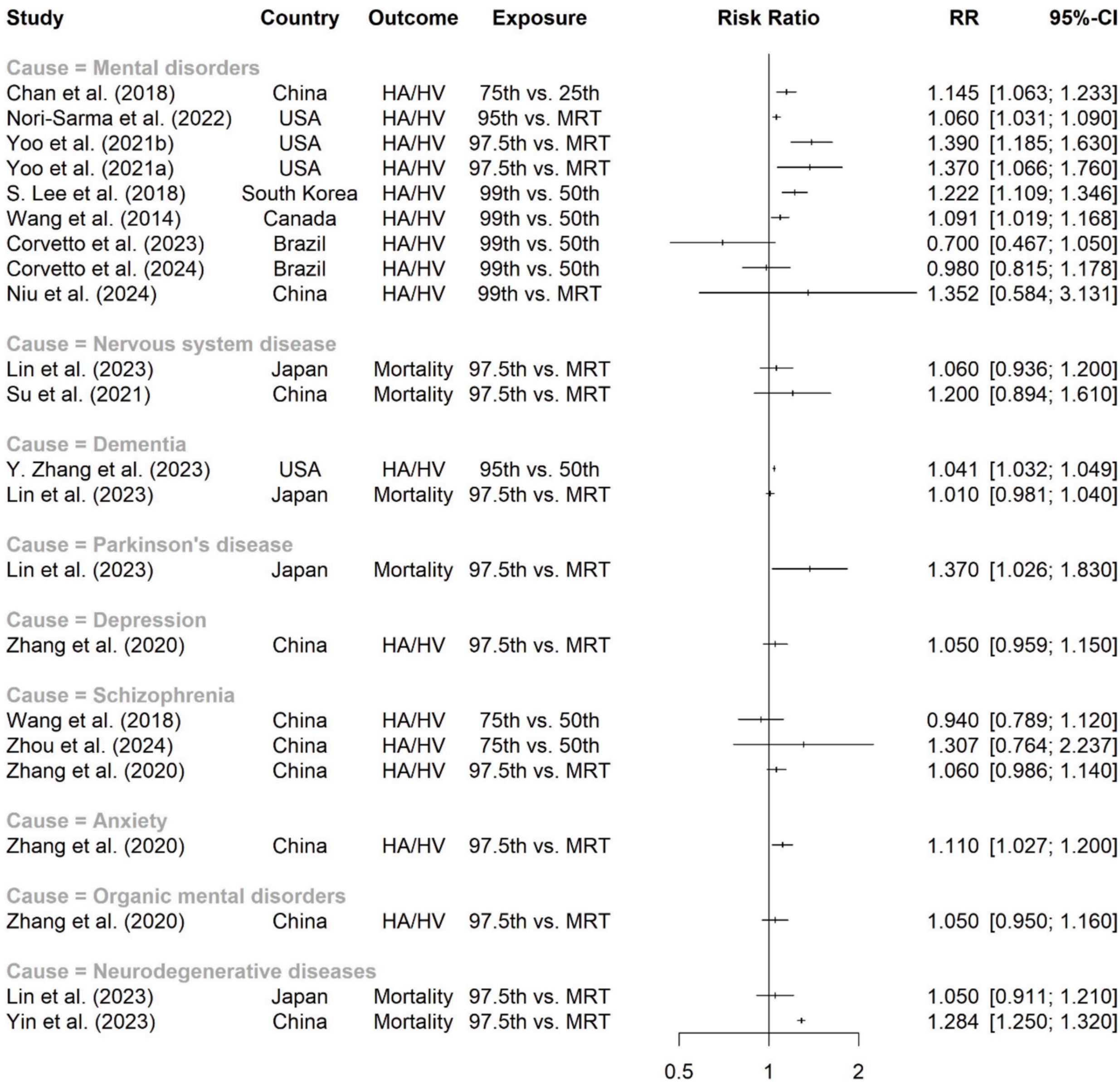

Fig. 4. Forest plot of the risk ratios for different mental and neurological conditions at a higher temperature percentile compared to a lower temperature percentile. *Note: HA/HV = hospital admissions or hospital visits; MRT = minimum risk temperature, which varies across studies.*

study of residents in Antarctica reported that cold temperatures may also stimulate the sympathetic nervous system, increasing the release of stress hormones like cortisol and catecholamines (Harinath et al., 2005). Elevated cortisol levels are associated with mood disorders and can exacerbate symptoms of depression and anxiety (Dziurkowska and Wesolowski, 2021). The hormonal responses induced by cold exposure could also be related to changes in cognitive performance in humans (Makinen et al., 2006).

Individuals with preexisting mental and neurological conditions may be more vulnerable to changes in ambient temperature compared to the general population. This heightened vulnerability may result from the maladaptive effects of psychiatric medications on thermoregulation, or a reduced capacity for behavioral adaptation, as individuals with these conditions may experience greater social isolation or communication barriers (Lohmus, 2018). Previous epidemiological studies have shown that individuals with mental or neurological conditions have a higher risk of heat-related mortality compared to the healthy population or those with other diseases (Astrom et al., 2015; Schifano et al., 2009; Stafoggia et al., 2008; Zanobetti et al., 2013).

4.4. Uncertainty and heterogeneity in studies

The collective evidence presented in this review was of moderate certainty. Although most studies were considered to have low or moderate RoB across the six domains evaluated, interpreting the RoB assessment warrants caution. Confounding was the most prevalent potential source of bias. A few long-term studies were identified as having a high RoB in this domain as they did not adjust for socioeconomic status. Socioeconomic status is often deemed a critical potential confounder in epidemiological studies due to its close relationship with health, yet it may not bias results if uncorrelated with the exposure in question, here being ambient temperature. While socioeconomic disparities in exposure could be present, they may not exist universally, as this varies depending on the study location and population (Osberghaus and Abeling, 2022; Renteria et al., 2022). In addition, studies categorized with low or moderate risk of confounding might still be prone to residual confounding by other factors not listed in the critical or additional potential confounders. RoB in other domains requires careful consideration as well. For instance, exposure assessment methods

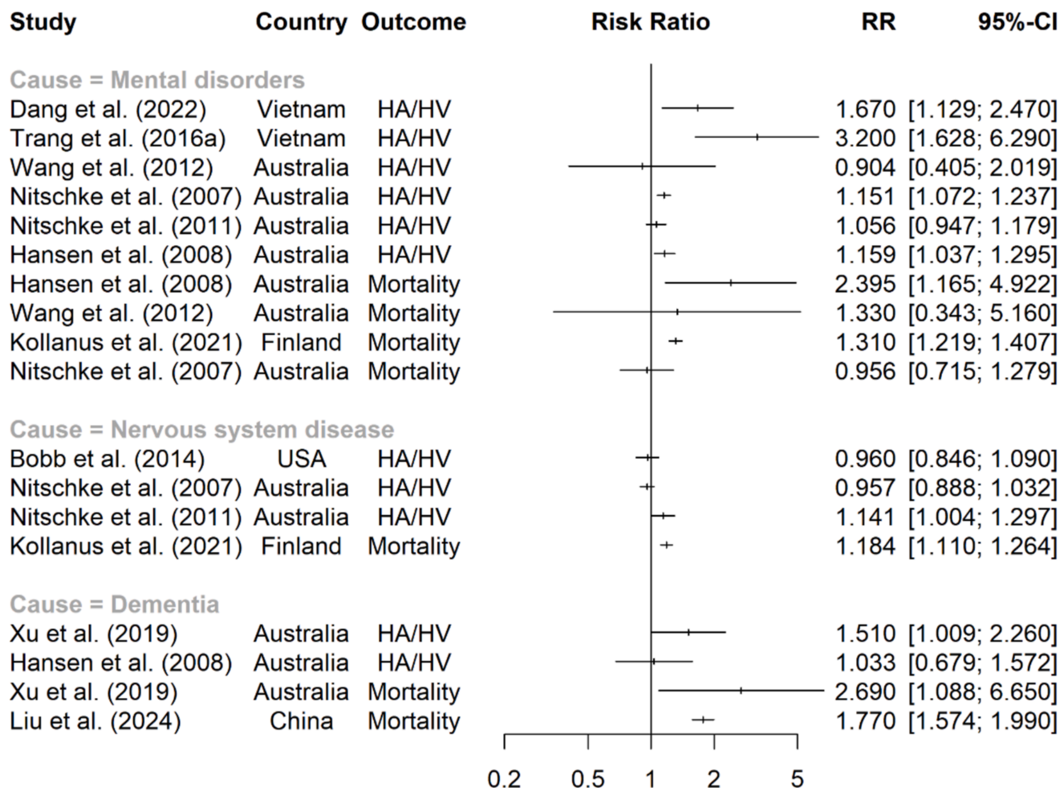

Fig. 5. Forest plot of the risk ratios for different mental and neurological conditions on heat wave days compared to non-heat wave days. *Note:* The definition *of heat wave varies across studies. HA/HV = hospital admissions or hospital visits.*

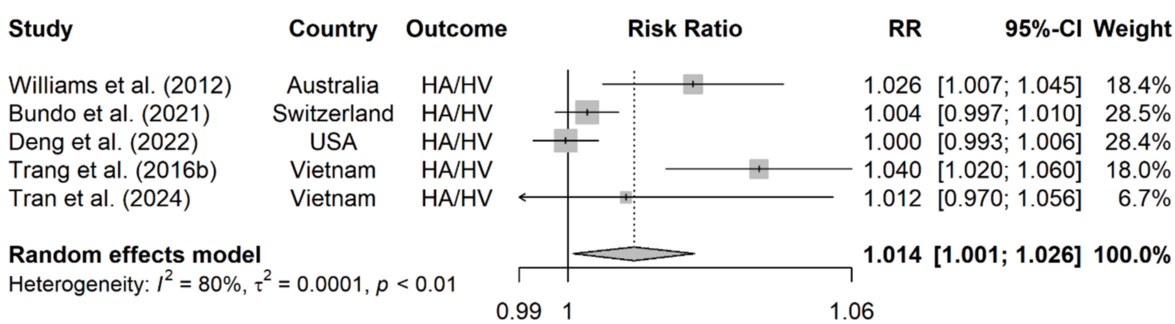

Fig. 6. Meta-analysis on the association of temperature (a 1 °C increase) with hospital admissions/visits for mental disorders. *Note: Effect estimates may be measured above a certain temperature threshold, which varies across studies.*

relying on monitoring stations were deemed low RoB, yet using city-average temperature instead of individual-level exposure assessment could lead to potential exposure misclassification. Further, even highly resolved exposure data, such as from gridded modeled temperature data, can incorporate uncertainties due to the use of estimates rather than measurements and participants' daily activity patterns.

Regarding inconsistency, there was notable heterogeneity in study variables and methodologies. Even within the same exposure metric, such as daily mean temperature, the methods to report effect sizes varied, including per 1 °C increase above a specified threshold or percentile-based effect estimates. Such heterogeneity may be seen as inevitable since the relationship between temperature and health often exhibits a non-linear pattern, with the shape of the exposure–response curve varying by region, population, or study period (Gasparrini et al., 2015; Guo et al., 2014; Son et al., 2019). Furthermore, various types of temperature-related exposure indicators exist, including extreme temperature events such as heat waves, apparent temperature, and temperature variability, without a consensus on a superior metric or standard definition for each. Studies included in the *meta*-analyses also showed significant heterogeneity in effect estimates, although the number of studies was limited. This heterogeneity could be due to differences in study locations and population characteristics, which were not further explored in this study. Nonetheless, the *meta*-analyses and the general trends observed in individual studies within this review consistently indicated adverse effects of non-optimum temperature exposures on a range of mental and neurological conditions among older adults.

4.5. Strengths and limitations

A key strength of this study is that, to our knowledge, this is the first systematic review and *meta*-analysis to encompass a broad range of mental and neurological conditions, particularly emphasizing neurodegenerative diseases in older adults who may be especially vulnerable to ambient temperature exposures. This study also examined a variety of temperature-related exposure metrics, such as cold exposure, apparent

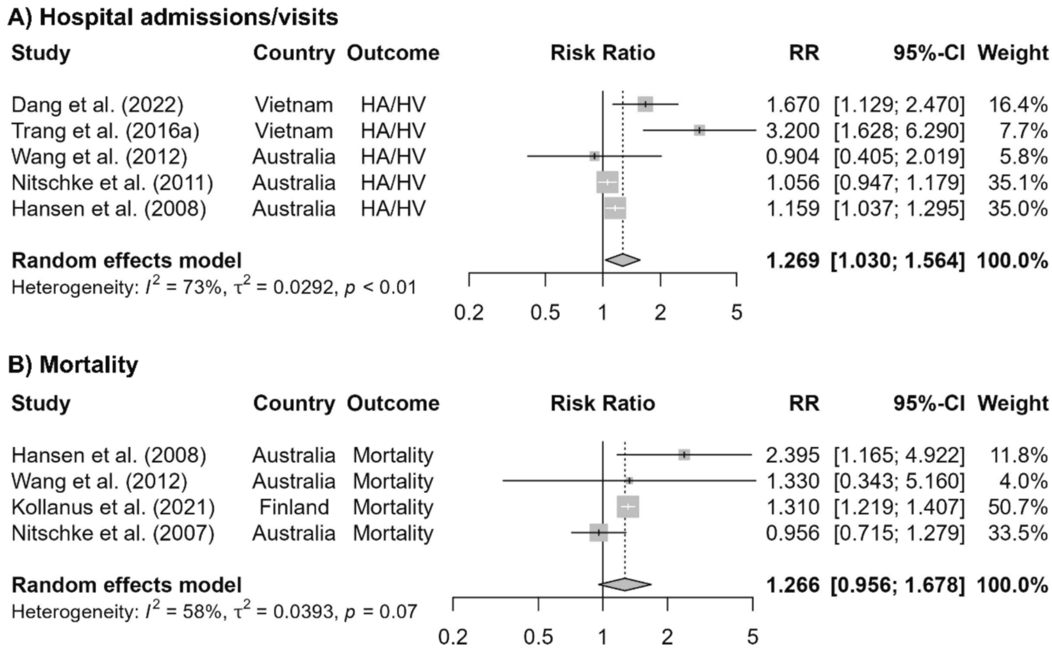

Fig. 7. Meta-analysis of the association between heat wave and hospital admissions/visits (Panel A) and mortality for mental disorders (Panel B). *Note: The definition of heat wave varies across studies.*

temperature, and temperature variability, areas that have received less attention in previous systematic reviews. Moreover, this study strictly followed Cochrane and PRISMA guidelines throughout the review process and in reporting findings and employed a thorough search strategy developed with the assistance of an experienced research librarian.

This study has several limitations that should be acknowledged. First, the study did not encompass all mental and neurological conditions, notably excluding substance abuse, self-harm, or suicide, which are significant aspects of mental health. Although these outcomes are typically seen in younger populations, they also affect older adults and may have important public health implications (Troya et al., 2019). Further research focusing on these conditions in older adults would be beneficial. Second, since this review specifically targeted mortality and morbidity resulting from mental and neurological conditions, it did not assess the susceptibility of individuals with these conditions to other health outcomes associated with temperature exposure. Third, the exclusion of grey literature and non-English publications means that unpublished dissertations, conference abstracts, or reports might have been overlooked if they were not published as journal articles. Fourth, considerable heterogeneity in exposure or outcome variables and methodologies among the studies prevented the application of *meta*-analyses across a broader range of studies, particularly for specific individual diseases. This also precluded the subgroup analyses by study region or population demographics to investigate sources of heterogeneity in the effect estimates. Additionally, studies used slightly different definitions of for heat wave and cold spell. These terms are generally defined by intensity (temperature) and duration (number of consecutive days) but there exists no standard definition in either science or policy. Since effect estimates of heat waves could be highly dependent on the definitions, especially in terms of intensity (Xu et al., 2016), the generalizability of the summarized results in this review may be limited. Fifth, most studies included in this review used time-series or case-crossover design. While these approaches are useful and important, daily mortality or hospital admissions may not fully reflect the onset of mental or neurological conditions. More studies using cohort or other designs could contribute to a better understanding of the causal relationship between temperature and these conditions. Although we present results as the “relative risk”, the analysis incorporates estimates for other formats (e.g., odds ratio). Finally, the evidence presented in this review predominantly came from high-income countries, limiting its generalizability to low- and middle-income countries.

4.6. Recommendations and implications

Considering these limitations, further studies are needed to strengthen the evidence base. Taking into account the potential non-linear relationship between temperature and health, exploring and synthesizing the exposure–response function between temperature and mental and neurological outcomes could offer a better understanding of these associations. As the effects of temperature on health vary by region, time period, and population, future work is needed to identify sources of heterogeneity or effect modifiers. Additionally, future review efforts might consider the vulnerability of individuals with existing mental and neurological conditions to temperature changes. In terms of individual studies, increased research on low- and middle-income countries, on various exposure metrics beyond high temperature and heat waves—such as cold spells and apparent temperature—and on specific diseases such as dementia or Parkinson’s disease, would be useful to fill the existing gaps in knowledge.

Climate change is anticipated to bring about not only a rise in average temperatures but also an increase in temperature variability, including more frequent and severe heat waves. Older adults are likely to be more susceptible to these changes compared to other age groups, facing a higher health burden from non-optimal temperatures in the near future. This study suggests that such health burdens are likely to include mental and neurological conditions, potentially leading to increased premature mortality, higher hospital utilization, and diminished quality of life and well-being among this demographic. The epidemiological evidence compiled in this review can inform the foundational basis for the development of adaptation strategies to address future climate change and the challenges of an aging population.

5. Conclusion

The epidemiological evidence gathered in this review highlights the negative impacts of non-optimum ambient temperatures on a variety of mental and neurological conditions in older adults. Meta-analyses revealed a significant increase in mortality and hospital visits/

Table 3
GRADE certainty of evidence rating and rationale.

Exposure	Domains for downgrading					Domains for upgrading			Overall	Final certainty assessment
	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Large effect	Dose-response	Opposing confounding		
High temperature	0 Most studies were rated as low or moderate RoB.	0 High heterogeneity was observed (I^2 = 85 %), but the variation in effect estimates was likely due to different study settings.	0 All studies made direct comparisons relevant to PECOS question.	0 Sample sizes were large enough.	0 No reliable evaluation was available.	0 The effect sizes were not large enough to upgrade.	1 Most studies observed an increase in risk of outcome with increasing temperature.	0 Residual confounding could occur in both directions.	+1	High
Heat wave	0 All studies were rated as low or moderate RoB.	0 Moderate heterogeneity was observed (I^2≈60 %), but the variation in effect estimates was likely due to different study settings	0 All studies made direct comparisons relevant to PECOS question.	0 Sample sizes were large enough.	0 No reliable evaluation was available	0 The effect sizes were not large enough to upgrade.	0 Not applicable for binary exposure.	0 Residual confounding could occur in both directions.	0	Moderate
Cold exposure	0 All studies were rated as low or moderate RoB.	0 Limited but consistent results were observed.	0 All studies made direct comparisons relevant to PECOS question.	0 Sample sizes were large enough.	0 No reliable evaluation was available.	0 The effect sizes were not large enough to upgrade.	0 There were an insufficient number of studies to upgrade.	0 Residual confounding could occur in both directions.	0	Moderate
Other metrics	0 All studies were rated as low or moderate RoB.	0 Limited but consistent results were observed.	0 All studies made direct comparisons relevant to PECOS question.	0 Sample sizes were large enough.	0 No reliable evaluation was available.	0 The effect sizes were not large enough to upgrade.	0 There were an insufficient number of studies to upgrade.	0 Residual confounding could occur in both directions.	0	Moderate

admissions related to mental disorders associated with high daily temperatures or heat waves. Despite methodological diversity among the studies, the trend of these associations remained broadly consistent, leading to an overall evidence base with moderate certainty. However, research remains sparse in low- and middle-income countries, for cold exposures, and within specific disease categories. The mental and neurological health of the older population requires increased focus within the broader discussions on climate change and the aging of the global population.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109166.

Data availability

Data will be made available on request.

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