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# The effects of radiofrequency exposure on cognition: A systematic review and *meta*-analysis of human observational studies

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ABSTRACT

*Background:* We aimed to assess evidence of long-term effects of exposure to radiofrequency (RF) electromagnetic fields (EMF) on indicators of cognition, including domains of learning and memory, executive function, complex attention, language, perceptual motor ability and social cognition, and of an exposure–response relationship between RF-EMF and cognition.

*Methods:* We searched PubMed, Embase, PsycInfo and the EMF-Portal on September 30, 2022 without limiting by date or language of publication. We included cohort or case-control studies that evaluated the effects of RF exposure on cognitive function in one or more of the cognitive domains. Studies were rated for risk of bias using the OHAT tool and synthesised using fixed effects *meta*-analysis. We assessed the certainty of the evidence using the GRADE approach and considered modification by OHAT for assessing evidence of exposures.

*Results:* We included 5 studies that reported analyses of data from 4 cohorts with 4639 participants consisting of 2808 adults and 1831 children across three countries (Australia, Singapore and Switzerland) conducted between 2006 and 2017. The main source of RF-EMF exposure was mobile (cell) phone use measured as calls per week or minutes per day.

For mobile phone use in children, two studies (615 participants) that compared an increase in mobile phone use to a decrease or no change were included in *meta*-analyses. *Learning and memory*. There was little effect on accuracy (mean difference, MD −0.03; 95% CI −0.07 to 0.02) or response time (MD −0.01; 95% CI −0.04 to 0.02) on the one-back memory task; and accuracy (MD −0.02; 95%CI −0.04 to 0.00) or response time (MD −0.01; 95% CI −0.04 to 0.03) on the one card learning task (low certainty evidence for all outcomes). *Executive function*. There was little to no effect on the Stroop test for the time ratio ((B-A)/A) response (MD 0.02; 95% CI −0.01 to 0.04, very low certainty) or the time ratio ((D-C)/C) response (MD 0.00; 95% CI −0.06 to 0.05, very low certainty), with both tests measuring susceptibility to interference effects. *Complex attention*. There was little to no effect on detection task accuracy (MD 0.02; 95% CI −0.04 to 0.08), or response time (MD 0.02;95% CI 0.01 to 0.03), and little to no effect on identification task accuracy (MD 0.00; 95% CI −0.04 to 0.05) or response time (MD 0.00;95% CI −0.01 to 0.02) (low certainty evidence for all outcomes). No other cognitive domains were investigated in children.

A single study among elderly people provided very low certainty evidence that more frequent mobile phone use may have little to no effect on the odds of a decline in global cognitive function (odds ratio, OR 0.81; 95% CI 0.42 to 1.58, 649 participants) or a decline in executive function (OR 1.07; 95% CI 0.37 to 3.05, 146 participants), and may lead to a small, probably unimportant, reduction in the odds of a decline in complex attention (OR 0.67;95%

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CI 0.27 to 1.68, 159 participants) and a decline in learning and memory (OR 0.75; 95% CI 0.29 to 1.99, 159 participants). An exposure–response relationship was not identified for any of the cognitive outcomes.
*Discussion:* This systematic review and *meta*-analysis found only a few studies that provided very low to low certainty evidence of little to no association between RF-EMF exposure and learning and memory, executive function and complex attention. None of the studies among children reported on global cognitive function or other domains of cognition. Only one study reported a lack of an effect for all domains in elderly persons but this was of very low certainty evidence. Further studies are needed to address all types of populations, exposures and cognitive outcomes, particularly studies investigating environmental and occupational exposure in adults. Future studies also need to address uncertainties in the assessment of exposure and standardise testing of specific domains of cognitive function to enable synthesis across studies and increase the certainty of the evidence.
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## 1. Introduction

*Rationale for a systematic review*.

Although mechanisms for potential effects of radiofrequency (RF) electromagnetic fields (EMF) at low levels are unknown, studies of cognitive performance in relation to RF-EMF exposure have been mainly motivated by concerns about the exposure of the brain during mobile (cell) phone calls. Possible acute effects of RF-EMF exposure on cognition have been evaluated in a range of experimental studies, but the experimental design cannot be used to study potential chronic effects of longer-term exposure on cognitive function (ARPANSA, 2014). Past reviews of human experimental and observational studies have generally been equivocal (Barth et al., 2008; Valentini et al., 2010; Regel and Achermann, 2011; Barth et al., 2012; Curcio, 2018; Ishihara et al., 2020). A systematic review is in progress evaluating the effects of RF-EMF on cognition in experimental studies (Pophof et al.,2021).

A review by Ishihara et al. (2020), was confined to possible cognitive effects of RF-EMF exposure in children and adolescents, but this review did include epidemiological studies evaluating longer term effects of RF-EMF in observational settings. The authors identified 12 eligible studies and found 86 % of extracted relationships were not statistically significant. They suggested the other 14 % of significant relationships may be chance findings. However, the vote-counting as employed by the Ishihara review is a flawed method that can lead to seriously biased conclusions as is stipulated in the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2023).

None of the previous observational evidence syntheses on the long-term effects of RF-EMF on cognition followed completely the recommendations for the conduct of systematic reviews in toxicology and environmental health research (COSTER) (Whaley et al., 2020).

## 2. Objectives

The primary objective of this review was to address the following PECO questions:

- What is the effect of long-term (months/years) RF exposure (E) on cognitive function (O) compared to no/low level of exposure (C) in the general population and workers (P) in human observational studies?

Secondary objective:

- Is there an exposure–response relationship between long-term levels of RF field exposure and cognitive function in men, women and children?

## 3. Methods

The methods for this systematic review and *meta*-analysis have been previously published (Benke et al., 2022) and are summarised below. The review is reported in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines (Page et al., 2021). The review was prospectively registered on PROSPERO CRD42021257548.

### 3.1. Eligibility criteria

#### 3.1.1. Types of studies and populations

General population and occupational studies, involving participants of any age or sex were eligible for inclusion. Studies were required to be either cohort or case-control in design, with the evaluation of either near and far field RF energy. Studies were excluded if they met any of the following criteria: 1) were not cohort or case-control designs; 2) investigated maternal exposure to RF during pregnancy and subsequent neurodevelopmental effects on the infant or child; 3) investigated neurodevelopmental disorders or neurodegenerative diseases; 4) outcomes measured with follow up from baseline $< 6$ months; and 5) comparator involved no lower level of RF exposure. We excluded cross-sectional studies since there was a lack of temporality in these studies and causal effects may be difficult to establish.

#### 3.1.2. Types of exposures

Studies were included that evaluated the effect of personal (near field), environmental (far field) or occupational exposures (near field/far field) to RF energy. Further, to be eligible, studies needed to compare at least two different levels of exposure intensity, frequency or duration, including a non-exposed group or a group with lower exposure. Studies published in any year and in any language were included.

The ideal exposure metric for RF-EMF would be a measure of the total dose (energy absorbed) in an appropriate target organ or tissue, which is a function of the specific absorption rate (SAR) and exposure duration and characteristics However, these quantities cannot be easily measured or modelled in an observational study setting. Instead, we included crude proxies of exposure – these may involve estimation of electric field strength in volts per metre (V/m) or power density in watts per metre squared ($W/m^2$), self-reported mobile or cordless phone use, or occupational information. Correlations between objective and personal self-reported data on mobile phone use have been previously reported (Vrijheid et al.,2009) and any misclassification would generally tend to bias results towards the nul, although differential bias cannot be ruled out. We did not include studies using self-reported distance to antennas or calculated distance to mobile phone base stations as these have been previously described as poor surrogates of exposure (Benke et al., 2022), but did include calculated distance to single location broadcast transmitters. Bias and complex propagation patterns have been previously described regarding these exposure metrics (Schmiedel et al, 2009; Frei et al.,2010). For occupational exposure we included studies where exposure was assessed by RF measurement, job-title or task, Job Exposure Matrices/Source Exposure Matrices or expert assessment.

#### 3.1.3. Types of outcomes

Studies were included that reported at least one measure of cognitive

function (or performance). The primary outcomes for the studies included were:

- global cognitive function
- domain-specific cognitive function including complex attention, executive function, learning and memory, language, perceptual-motor ability and social cognition.

We expected definitions and measures of cognitive function to vary across studies, so we accepted a range of definitions. The tests or diagnostic criteria used in each study should have had evidence of validity and reliability for the assessment of cognitive function but not be related to neurodegenerative disorders. Results may have been reported as an overall test score that provides a composite measure across multiple areas of cognitive ability (i.e. global cognitive function), sub-scales that provide a measure of domain specific cognitive function or cognitive abilities (e.g. complex attention, memory), or both.

### 3.2. Information sources and search strategy

We searched PubMed, Embase, PsycInfo and the EMF-Portal (RWTH, Aachen University) on September 22, 2021 and repeated the same searches on September 30, 2022, without limiting by date or language of publication. The search strategy for PubMed combined Medical Subject Headings (MeSH) and text word terms for the exposure and outcome limited to human observational studies, and was translated for Embase and PsycInfo, incorporating the relevant database thesaurus terms for radiofrequency, cognition and study design (**Supplemental File S1**).

We examined seven literature reviews (published between 2004 and 2015 by leading international and national government agencies) addressing the health effects of exposure to RF in general and extracted the subset of studies that related to cognitive effects and screened these for eligibility along with records from the database searches (**Supplemental File S1**).

We checked the websites of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), International Commission on Non-Ionizing Radiation Protection (ICNIRP), Public Health England, Scientific Committee on Emerging and Newly Identified Health Risks, Swedish Radiation Safety Authority, and Health Council of the Netherlands for any unpublished reports or research not identified in our searches. We also screened records supplied to us by the secretariat of the Radiation and Health Unit at the World Health Organization (WHO). Finally, we checked the references of all eligible studies to identify any additional studies not previously retrieved.

### 3.3. Selection process

Four review authors (CB, KK, GB or BZ) screened the titles and abstracts of all records in Covidence (two of the four authors independently screened each record), with any screening conflicts resolved by consensus among the team. Full-text screening was also done independently by two review authors (CB, KK) with conflicts resolved by consensus among the team. During full-text screening multiple reports of the same study were identified and linked e.g. by using cohort names, author names, study titles, locations and dates. For studies with multiple reports, we extracted data from all reports, where relevant, to obtain the most complete data for outcomes measured at various time points. Reports published in languages other than English were screened by the review team (German) or with the help of colleagues (Chinese).

### 3.4. Data collection process

Six review authors (BZ, CB, GB, HK, KK, MA) extracted data on the characteristics of studies and results using a pre-piloted data extraction form (Brennan et al., 2020); two of the six authors independently extracted the data for each included study. Discrepancies were resolved through discussion among the team where methodological or content advice was required. Review authors did not extract or assess risk of bias for any study on which they were an author. The data extraction included study identifiers and characteristics of the study design, characteristics of the exposure and comparator groups, and participant characteristics. We intended to contact authors of articles for missing data needed in the analysis, however this was not required.

### 3.5. Risk of bias assessment

We used the Risk of Bias Rating Tool for Human and Animal Studies by the NTP Office of Health Assessment and Translation (OHAT) (NTP, 2019; Rooney et al., 2014). Five review authors (KK, CB, BZ, MA and HK) assessed the risk of bias of the results from the included studies; two of the five authors independently assessed the risk of bias for each included study. Discrepancies were resolved through discussion.

For each study we assessed the following domains: selection bias, confounding, attrition/exclusion bias, bias in the characterisation of exposures, bias in the assessment of outcomes, bias in selection of the reported results, and other threats to validity including financial conflicts of interest.

Within each bias domain, we judged risk of bias as "definitely low" (direct evidence of low risk of bias practices), "probably low" (indirect evidence of low risk of bias practices, or deviations from low risk of bias practices unlikely to appreciably bias results), "probably high" (indirect evidence of high risk of bias practices or insufficient information) or "definitely high" (direct evidence of high risk of bias practices). Our judgement of the overall risk of bias for each result was based on the most serious risk of bias judgement across any of the bias domains (i.e. overall risk of bias is "probably high" if at least one key domain is rated "probably high"). We also tabulated domain-level judgements for each study, reporting the tiers of study quality (1, 2 and 3 where 1 reflects studies at lowest risk of bias), described in the OHAT handbook (OHAT, 2019). We focused on four key-items including selection/attrition biases, and exposure/outcome detection biases. Tier-1 comprised studies with definitely or probably low risk of bias for all key-items and most of other items; tier-3 included studies with definitely or probably high risk of bias for all key-items and most of other items; and studies that did not meet the criteria for tier-1 or tier-3 were classified as tier-2. We considered these tiers when judging the overall risk of bias for each result when assessing confidence in the evidence.

### 3.6. Effect measures

We expected that cognition would be measured using long continuous or ordinal scales, with varying measurement instruments used across studies. Where possible, we reported mean differences (MD) as the effect size. When similar constructs were measured with different scales, the standardised mean difference (SMD) was used as the measure of effect. In the circumstance where results from multiple multivariable models were presented, we extracted effects from the most fully adjusted model, except in the case where an analysis adjusted for a possible intermediary along the causal pathway i.e. post baseline measures of prognostic factors, such as smoking, education (Karahalios et al., 2017). For ordinal measures of cognition that were dichotomised and analysed as binary outcomes in the primary studies, we intended to re-express reported or calculated odds ratios (ORs) as SMDs (Chinn, 2000), however, only one study reported ORs so we did not use this transformation. We used Cohen's guiding rules for interpreting MDs or SMDs where −0.2 to 0.2 represents a trivial effect ('little to no difference'), 0.2 a small effect, 0.5 a moderate effect, and 0.8 a large effect (Schuneman et al., 2019). For odds ratios, we considered whether relative effects indicated an important effect (an OR $> 1.25$ or $< 0.80$) and confirmed this interpretation by calculating the absolute risk difference (using an ARD of 5 % as an important effect).

### 3.7. Synthesis methods

We first compared the highest exposure group versus the lowest exposure group. We then compared the incremental risk increase from one unit of exposure compared to a lower unit of exposure. We intended to conduct a *meta*-analysis of similar studies with random effects models if two or more studies were available for a given exposure-outcome combination. However, because only two studies were available from the same research group we followed the recommendation of Bender et al (2018) and conducted a fixed effects *meta*-analysis in StataSE (Ver 18, StataCorp, College Station, TX); pooled estimates were combined in forest plots. We considered studies that included only children or adolescents separately from those that included only adults (in subgroups within each analysis).

We assessed heterogeneity through visual inspection of the study-specific exposure −response curves. Formal testing for heterogeneity was conducted using the $\chi^2$ test (using a significance level of $\alpha = 0.1$), and we quantified heterogeneity in the study-specific exposure −response coefficients using the $I^2$ statistic.

### 3.8. Assessment of reporting biases

We planned to assess the risk of bias due to missing results (publication bias) following the framework described in the Cochrane handbook (Page, 2020). The framework includes an assessment of whether results for eligible outcomes were unavailable despite data being collected by included studies, and whether results from additional studies were likely to be missing (the study was not published or was missed in the search). In practice, the information required for these assessments was not available (registry entries, detailed protocols) and we had too few studies to prepare funnel plots or conduct tests of funnel plot asymmetry.

### 3.9. Certainty assessment

We assessed the certainty of the results of the body of evidence from the exposure–response analysis of the studies using the GRADE approach and considering modification by OHAT for assessing evidence of exposures (detailed in the review protocol, Benke et al., 2022; see section 3.6 for thresholds for assessing certainty). A judgement was made about whether there are concerns that decrease (or increase) confidence in the estimated association based on an assessment of the following domains: risk of bias, unexplained inconsistency, imprecision, indirectness, publication (reporting) bias, upgrading domains (e.g. large effect size, bias toward null) (OHAT 2019, Schunemann 2013, Schunemann, 2018).

An evidence summary table (evidence profile) was prepared as per GRADE guidance. Using OHAT decision rules, we derived an overall rating of the certainty in the evidence for each result included in the summary of findings table. Result from a body of evidence comprised of eligible observational studies began as 'low' to 'moderate' certainty evidence (score = 3, reflecting an automatic downgrade for concerns about risk of bias arising from confounding and selection of participants into the study), and could be rated down (−1 or −2) for serious or very serious concerns on any domain that reduced confidence that RF-EMF had a health effect (as determined by the pre-specified thresholds). The initial confidence rating of low or moderate was determined based on the presence (or absence) of the following key study design features: (1) assessment of exposure that represented exposures prior to the development of the outcome, (2) outcome assessment at individual-level, and (3) an appropriate comparator group. Where all three features were present, the initial rating of the evidence was moderate confidence.

## 4. Results

### 4.1. Study selection

The search retrieved 3945 unique records for screening. Of these 3625 records were deemed irrelevant at title/abstract screening. We examined the full text of 320 reports, of which five studies (published in 10 reports) were included in the review (Thomas et al., 2010; Ng et al., 2012; Roser et al., 2016, Bhatt et al., 2017; Foerster et al., 2018). Reasons for exclusion at the full-text stage were tabulated by study and summarised in the **Supplemental File S2**. PRISMA flow diagram (Fig. 1).

### 4.2. Study characteristics

All the studies included were prospective cohort studies with a length of follow-up of approximately one year, apart from one study (Ng et al., 2012) that had a follow-up of nearly four years. One paper was excluded (Schoeni et al., 2015), due to the later Foerster paper recruiting a second wave of participants and incorporating data from both the original participants of Schoeni et al. and those recruited in the second wave into their analysis, and which reported findings 2 years later. These studies examined the same outcomes (figural and verbal memory). Further, the participants from the Roser et al., 2016 study were also incorporated into the later Foerster paper, however, this study was included as different outcomes were measured (concentration capacity instead of figural and verbal memory). The characteristics of participants, exposures and outcomes in the studies included are summarised in Table 1. Detailed study characteristics are described in **Supplemental File S3**.

Participants in all except one study (Ng et al., 2012) were children or adolescents; the subjects in the Ng et al. (2012) study were older adults all 55 years or older.

All the included studies investigated the effect of personal exposure, mainly mobile and cordless phone use. One of the children studies (Roser et al.,2016) also investigated environmental exposure. No study investigated occupational exposure.

Complex attention and learning and memory were investigated in 4 studies each (Thomas et al., 2010; Bhatt et al., 2017; Ng et al., 2012; Roser et al., 2016, complex attention; Foerster et al.,2018, learning and memory). Executive function was investigated in 3 studies (Thomas et al., 2010; Bhatt et al., 2017; Ng et al., 2012), whilst global function and perceptual motor ability were investigated in one study for each (Ng et al., 2012, and Thomas et al., 2010, respectively). None of the studies investigated language, perceptual motor ability and social cognition.

### 4.3. Risk of bias in studies

Overall risk of bias was rated as probably high in three of the included studies and probably low in the remaining two studies (see Table 2). The Thomas et al (2010) and Bhatt et al (2017) studies were both rated as probably high risk of detection bias because exposure to RF EMF was assessed indirectly via self-reported wireless phone use. The Roser et al (2016) and Foerster et al (2018) studies which were similar and included self-reported wireless phone use also applied various other methods of assessing exposure including calculating the brain dose of RF EMF which was developed by validating self-reported information through operator records; these studies were therefore rated as probably low risk of bias. The Ng et al. (2012) study was rated as probably high risk of attrition/exclusion bias because only 31 % of participants provided baseline data (and thus could be included in the analysis). Furthermore, of these participants not all completed all the neuropsychological tests. Outcome data were therefore largely incomplete and not adequately addressed by the authors. Finally, exposure was self-reported mobile phone use and the study did not estimate the intensity and duration of RF exposure from the time spent using a mobile

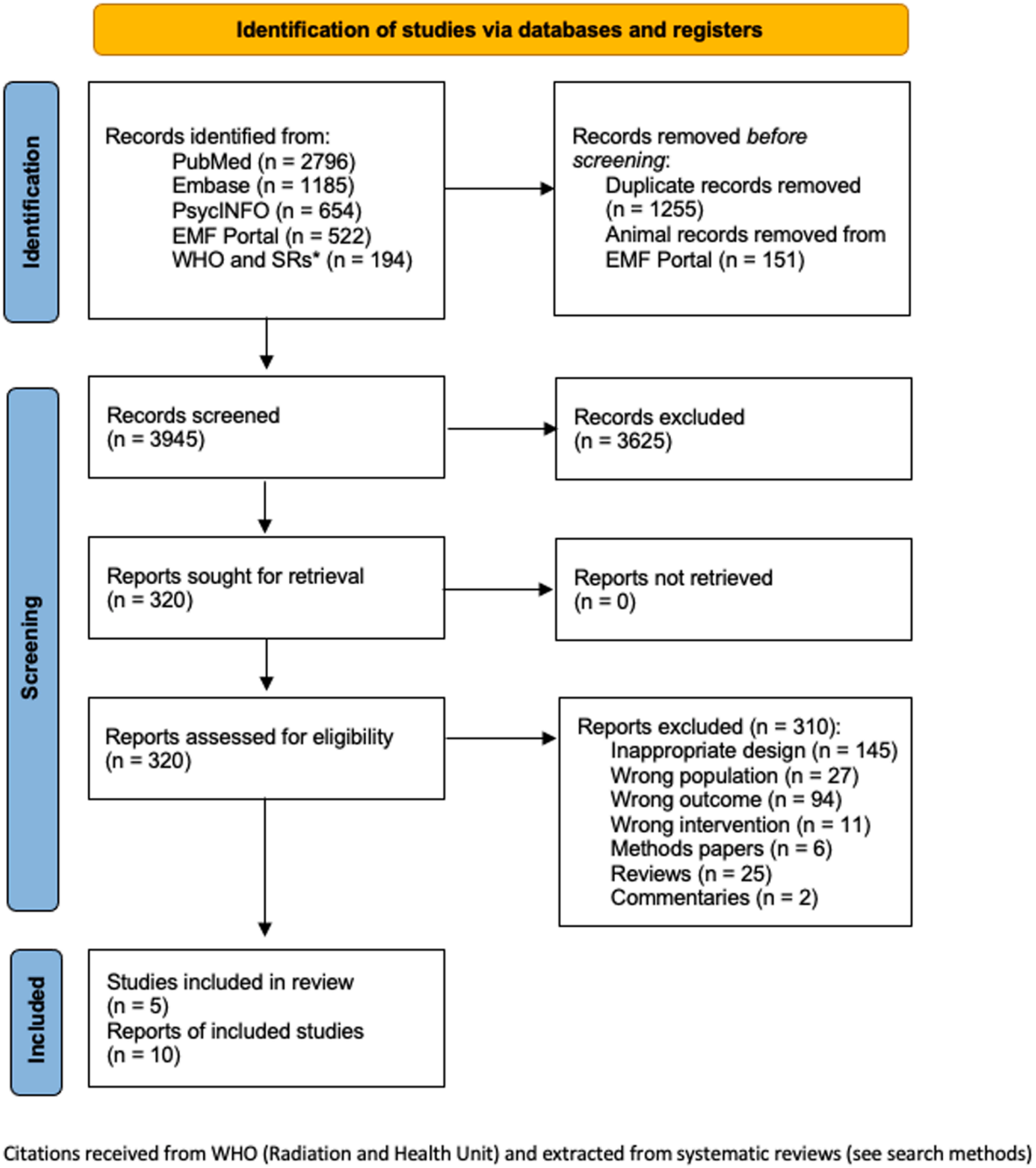



**Fig. 1.** PRISMA flow diagram.

phone and years of "mobile phone use", so the detection bias for the exposure was assessed as probably high. Detailed risk of bias assessments for individual studies are available in **Supplemental File S4**.

### 4.4. *Effects of the exposure*

A. Effects of RF-EMF personal exposure in children

*0A.1. Effects on global cognitive function in children:*

None of the eligible studies assessed global cognitive function in children.

*0A.2 Effects on complex attention in children:*

*A meta*-analysis of two studies was possible (Thomas et al., 2010; Bhatt et al., 2017). The MD for a decrease or same number of calls per week compared to an increase in calls per week for the test score on the detection task (simple reaction time test) for accuracy after one year of follow-up was 0.02 (95 %CI −0.04 to 0.08); $I^2 = 0$ %; 2 studies, 615 participants (Fig. 2). In both studies there was an increase of 25 % in the median number of calls from baseline to follow-up.

For the same exposure contrast and follow-up time, the test score on the identification task (choice reaction time test) for accuracy was MD 0.00 (95 %CI −0.04 to 0.05) $I^2 = 0$ %; 2 studies, 615 participants. The test score on the detection task for response time was MD 0.02 (95 %CI 0.01 to 0.03); $I^2 = 63$ %; 2 studies, 615 participants. The test score on the

**Table 1**
Overview of characteristics of studies that examined the effect of different levels of RF-EMF exposure.

| Study | Country | Participants | | | RF Exposure | | Cognitive function | Outcome description |
|---|---|---|---|---|---|---|---|---|
| | | Sample size (% Female) | Age at baseline (Years) | Length of follow up | Personal | Environmental | | |
| HERMES Roser et al. (2016) | Switzerland | 493 students enrolled at baseline (60 % female) | 14 (12 to 17) Mean (range) | 12.8 months | Mobile self-reported; Mobile Operator; Cordless self-reported; Calculated Dose | Personal Measurements | Complex attention | **SCD: Concentration capacity** Homogeneity, power and accuracy of concentration from FAKT-II battery |
| HERMES Foerster et al. (2018) | Switzerland | 895 participants enrolled at baseline (56 % female) | First wave (14.0 ± 0.85) (Roser et al., 2016 participants) Second wave (14.1 ± 0.86) Mean ± SD | ~1 year | Mobile self-reported; Mobile Operator; Cordless self-reported; Calculated Dose | | Learning & Memory | **SCD: Verbal memory** (Accuracy of recall in 1 min of wording, using semantic categories) **Figural memory** (Accuracy of performing a figural matching task in 1 min) |
| MoRPhEUS Thomas et al. (2010) | Australia | 317 students enrolled at baseline (55 % female) | 12.9 (11.7 to 14.3) Mean (IQR) | ~1 year | Mobile self-reported | | Complex Attention; Executive Function; Learning & Memory; Perceptual motor ability | **SCD: Signal detection** (response time and accuracy for simple and choice reaction test); **Working memory** (response time and accuracy to one-back and two-back task); **Learning** (response time and accuracy to one-card learning and associative learning tasks); **Psychomotor performance** (response time and accuracy to movement monitoring task); |
| EXPOSURE Bhatt et al. (2017) | Australia | 619 students enrolled at baseline (53 % female) | 10 ± 0.4 Mean ± SD | 1.03 ± 0.17 years | Mobile self-reported; Cordless self-reported | | Complex Attention; Executive Function; Learning & Memory | **SCD: Signal detection** (response time and accuracy for simple and choice reaction tests); **Working memory** (response time and accuracy to one-back task); **Learning** response time and accuracy to one card task (visual recognition memory and attention), Go/No-Go (response inhibition), and Groton maze learning task (spatial and executive ability) **Executive function** response time and time ratios to Stroop Colour-Word test (ability to inhibit cognitive interference when processing stimulus characteristics) |
| SLAS Ng et al. (2012) | Singapore | 2808 (871 participants (66 % female) completed baseline and follow up) | 65.2 Mean | 3.88 years | Mobile self-reported | | Global Function; Complex Attention; Executive Function; Learning & Memory | **GCF** (MMSE score); **SCD: Attention and working memory** (Z scores of Verbal attention, Spatial attention and Total attention); **Memory** (Z scores of Verbal memory, Spatial memory, Total memory); **Executive function** (Z scores Design fluency, Total executive function). |

SCD: Specific Cognitive Domain; SLAS: Singapore Longitudinal Ageing Studies; HERMES: Health Effects Related to Mobile phonE use in adolescentS; MoRPhEUS: Mobile Radiofrequency Phone Exposed Users' Study; ExPOSURE: Examination of Psychological Outcomes in Students Using Radiofrequency dEvices; FAKT-II: Frankfurter Adaptive Konzentrationsleistungs-Test-II.

identification task for response time MD 0.00 (95 % −0.01 to 0.02); $I^2 =$ 8 %; 2 studies, 615 participants. Results from the two studies were consistent for both measures of accuracy. For both measures of response, the direction of association suggested an increase in cognitive function in one study and a decrease in the other, but the inconsistency was likely to be unimportant because the effect size was trivial in both studies and the confidence intervals overlapped.

One other study (Roser et al., 2016) measured the complex attention in children with a different test, the Frankfurter Adaptive Konzentrationsleistungs-Test-II (FAKT-II) and was not included in the *meta*-analysis. The Roser et al (2016) study conducted a longitudinal analysis and found a SMD for accuracy of concentration of −0.4 (95 %CI −0.95 to 0.16) per interquartile range of minutes per day of self-reported mobile phone use; 290 participants. The same study found a SMD for cumulative RF-EMF brain dose and accuracy of concentration of −0.13 (95 %CI −0.68 to 0.42).

*0A.3 Effects on executive function in children.*

A *meta*-analysis of two studies was possible (Thomas et al., 2010;

**Table 2**
Risk of bias for included studies.

| Author (year) | Selection Bias | Confounding and modifying variables | Outcome data attrition or exclusion Bias | Detection Bias for exposures | Detection Bias for outcomes | Outcome Reporting Bias | Overall Bias | Tier of study quality |
|---|---|---|---|---|---|---|---|---|
| Thomas et al. (2010) | Probably Low | Probably Low | Probably Low | Probably High | Probably Low | Definitely Low | Probably High | 2 |
| Bhatt et al. (2017) | Definitely Low | Probably Low | Probably Low | Probably High | Probably Low | Probably Low | Probably High | 2 |
| Roser et al. (2016) | Definitely Low | Probably Low | Probably Low | Probably Low | Definitely Low | Definitely Low | Probably Low | 1 |
| Foerster et al. (2018) | Definitely Low | Probably Low | Probably Low | Probably Low | Definitely Low | Probably Low | Probably Low | 1 |
| Ng et al. (2012) | Probably Low | Probably Low | Probably High | Probably High | Definitely Low | Probably Low | Probably High | 2 |

Bhatt et al., 2017) The MD result for a decrease or same number of calls per week compared to an increase in calls per week for the score on the Stroop test (B-A/A) (measuring susceptibility to interference effects, Stroop, 1935) response time after one year of follow-up was MD 0.02 (95 %CI −0.01 to 0.04), $I^2 = 88$ %; 2 studies, 612 participants (Fig. 2).

For the same exposure contrast, the score on the Stroop test (D-C/C) (also measuring susceptibility to interference effects) response time after one year follow up was MD 0.00 (95 %CI −0.06 to 0.05), $I^2 = 59$ %; 2 studies, 612 participants. The results were importantly inconsistent for one measure ((B-A)/A), with the studies showing the opposite direction of association (one an increase in cognitive function, the other a decrease) and no overlap in the confidence intervals. For the second measure ((D-C)/C), the direction of association suggested an increase in cognitive function in one study and a decrease in the other, but the inconsistency was likely to be unimportant because the confidence intervals overlapped.

*0A.4 Effect on learning and memory in children.*

A *meta*-analysis of two studies was possible (Thomas et al., 2010; Bhatt et al., 2017). The MD result for a decrease or same number of calls per week compared to an increase in calls per week for the test score on Working Memory (CogHealth one back test, accuracy) after one year of follow-up was MD −0.03 (95 %CI −0.07 to 0.02), $I^2 = 66$ %; 2 studies, 615 participants. The test score for the response time of the same test was MD −0.01 (95 %CI −0.04 to 0.03), $I^2 = 70$ %. The test scores for the one card learning test (visual recognition memory and attention test) were MD −0.02 (95 %CI −0.04 to 0.00), $I^2 = 0$ %, for accuracy and MD −-0.01 (95 %CI −0.04 to 0.03), $I^2 = 70$ %, for response time; 2 studies, 615 participants. The results from the two studies were consistent for one measure of accuracy (one-card learning) and both measures of response. For the second measure of accuracy (one-back memory), the direction of association suggested an increase in cognitive function in one study and a decrease in the other, but the inconsistency was likely to be unimportant because the confidence intervals overlapped.

The Foerster et al. (2018) study compared the effect of exposure per interquartile range of minutes per day of self-reported mobile phone use on the test-score of the Intelligenz-Struktur-Test (IST) for verbal memory and found a SMD −0.01 (95 % CI −0.29 to 0.27, 676 participants), and a SMD −0.21 (95 % CI −0.51 to 0.09, 670 participants) for figural memory (see Table 3). However, although the Foerster et al (2018) study showed an absence of any effects on verbal memory, it found a decreased figural memory score in association with increased cordless phone calls and increased estimated cumulative RF-EMF brain scores (see Table 3).

*0A.5 Effects on other domains in children.*

None of the included studies assessed effects on language, perceptual and motor ability, social cognition, or clinical diagnoses in children.

B. The effects of RF-EMF environmental exposures in children

*B1. Effects on global cognitive function*

None of the eligible studies investigated the effects of RF-EMF environmental exposure and global cognitive functioning in children.

*B2. Effects on complex attention*

In one study, for complex attention measured using the FAKT-II test (Roser et al., 2016), the SMD for total personal RF EMF exposure (with mean total exposure of 66.8 μW/m2) and accuracy of concentration was −0.09 (95 %CI −0.76 to 0.57), 79 participants..

*B3. Effects on other domains* in children.

None of the eligible studies assessed RF-EMF environmental exposure and executive function or learning and memory, perceptual and motor ability in children, social cognition or clinical diagnoses in children.

C. The effects of RF-EMF personal exposure in elderly people

*C1. Effects on global cognitive function in elderly people.*

One study (Ng et al., 2011) evaluated the effect of self-report of using a mobile phone sometimes (>1 call per week but not daily) or often (daily, ≥ 7 calls per week) compared to never/rarely (<1 call per week) in adults and elderly people on global cognitive function measured with the Mini Mental State Examination (MMSE). Scores on the MMSE were dichotomised (change from baseline of 1.5 standard deviation or more = cognitive decline), and effects reported as an odds ratio. During a follow-up period of 4 years the odds of cognitive decline were lower among those who used mobile phones 'sometimes' (OR 0.67;95 % CI 0.34 to 1.30, 222 participants) or often (OR 0.81; 95 % CI 0.42 to 1.58, 269 participants) compared to never or rare use. Both results were of very low certainty due to risk of bias and imprecision.

*C2. Effects on complex attention in elderly people.*

In the same study by Ng et al. (2011), the odds of decline in complex attention were lower among those who used mobile phones 'sometimes' (OR 0.48;95 %CI 0.16 to 1.45, 42 participants) or 'often' (OR 0.67;95 % CI 0.27 to 1.68, 80 participants) compared to never/rare use. Both results were of very low certainty due to risk of bias and imprecision.

*C3. Effects on executive function in elderly people.*

Ng et al. (2011) also found that the odds of decline in executive function were higher among those who used mobile phones 'sometimes' (OR 1.87;95 %CI 0.62 to 5.61, 40 participants) and similar among those who used mobile phones 'often' (OR 1.07; 95 %CI 0.37 to 3.05, 77 participants) compared to never/rare use. Both results were of very low certainty due to risk of bias and imprecision.

*C4. Effects on learning and memory in elderly people.*

The study by Ng et al. (2011) also found that the odds of decline in learning and memory were lower among those who used mobile phones 'sometimes' (OR 0.90; 95 %CI 0.33 to 2.50, 48 participants) or 'often (OR 0.75; 95 %CI 0.29 to 1.99, 77 participants) compared to never/rare use. Both results were of very low certainty due to risk of bias and imprecision.

*C5. Effects on other domains in elderly people.*

None of the eligible studies investigated the effects of RF EMF exposure on perceptual and motor ability, on social cognition or on clinical diagnosis in elderly people.

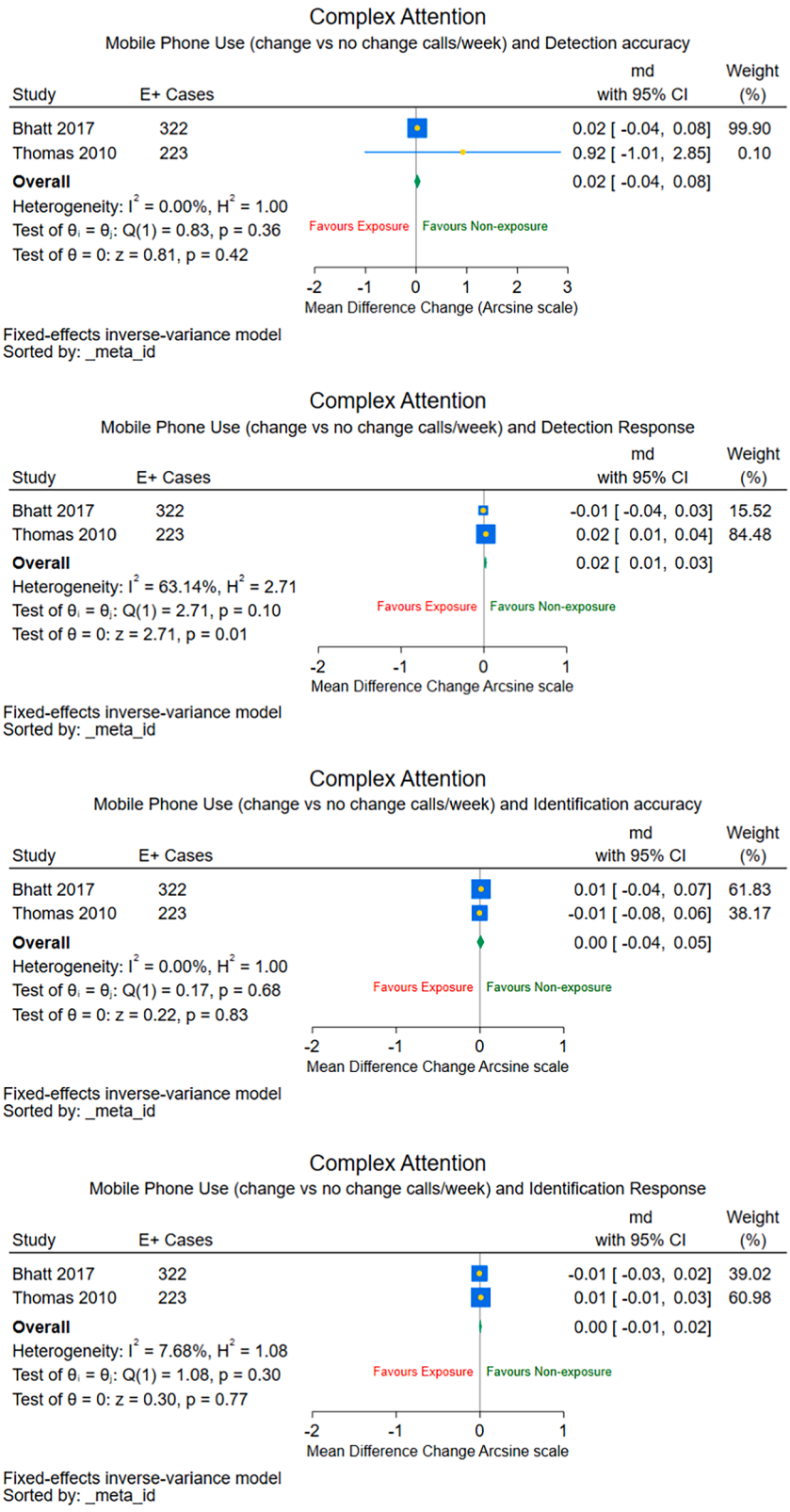


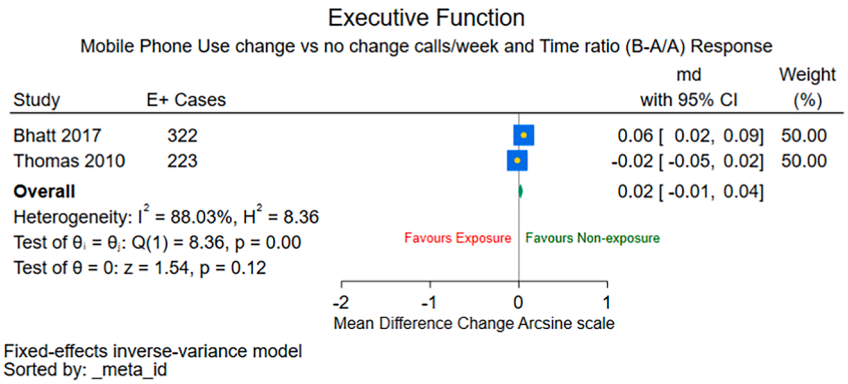

**Fig. 2.** Forest plots for complex attention, executive function and learning and memory for the Bhatt et al and Thomas et al studies.

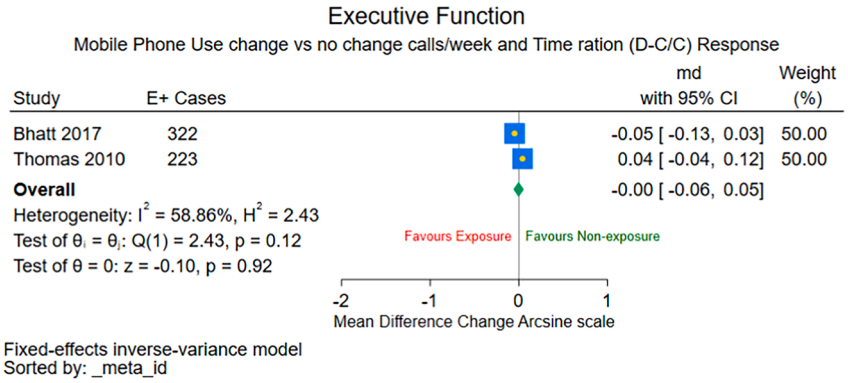
D. The effects of RF EMF environmental exposure in elderly people

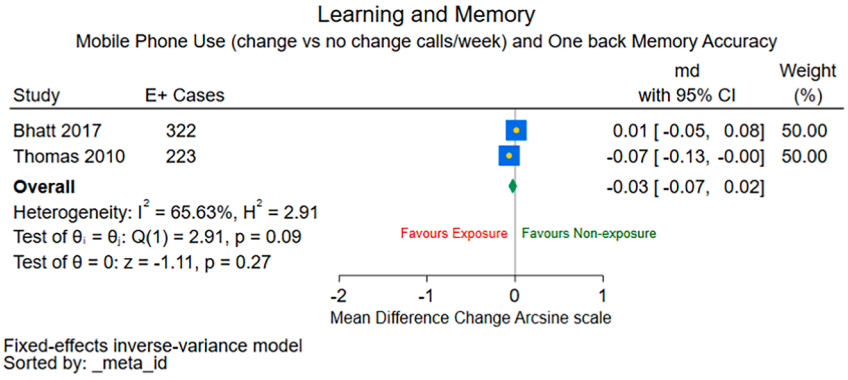
There were no eligible studies that investigated the effects of RF EMF environmental exposure on cognitive function in elderly people.

E. The effects of RF EMF occupational exposure in adults

There were no eligible studies that investigated the effects of RF EMF occupational exposure on cognitive function in adults.



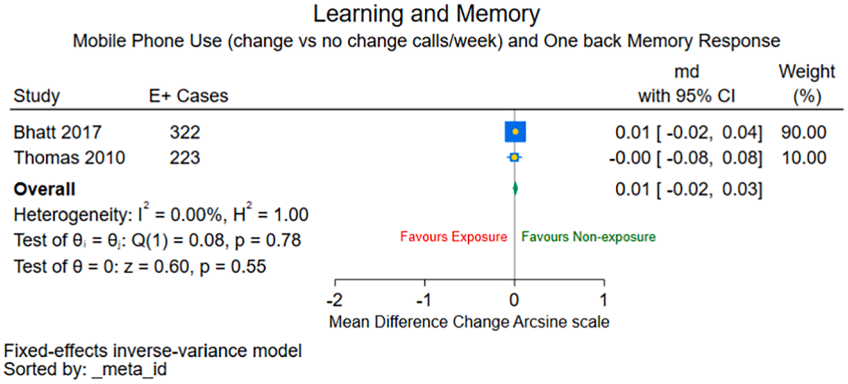




**Fig. 2.** (*continued*).

### 4.5. Results of individual studies

The results of individual studies can be found in **Supplemental File S5**.

## 5. Discussion

### 5.1. Summary of the evidence and interpretation of the results

A Summary of Findings table (SoF) has been provided in Table 3 detailing the findings of the GRADE analysis. The results can be

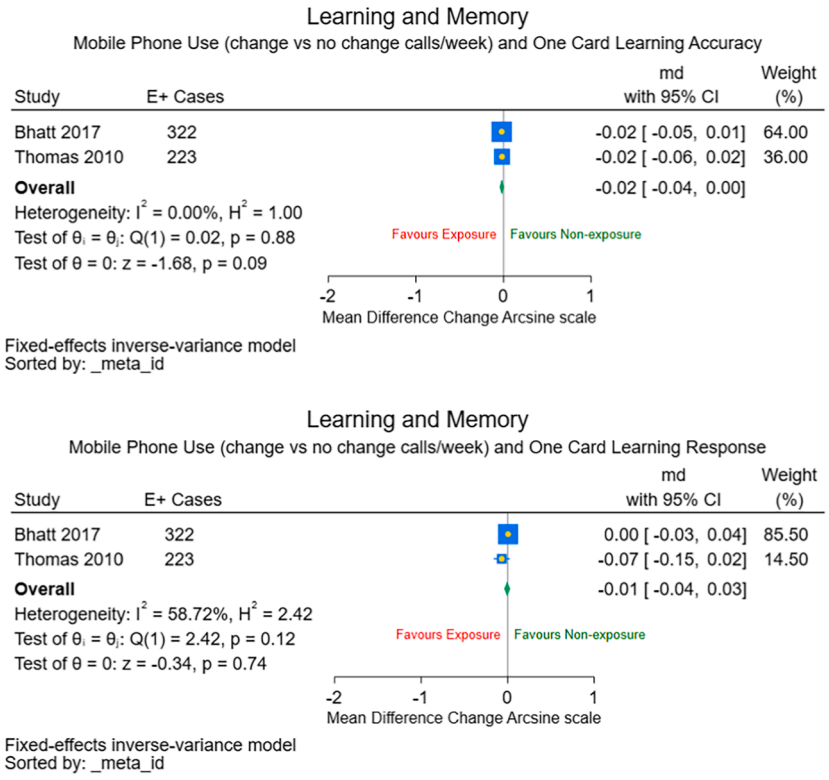



**Fig. 2.** (*continued*).

summarised as follows:

In children, for personal RF-EMF exposure, we found no effect in the results of the tests in the *meta*-analysis for complex attention with the detection task, or identification task with low certainty evidence. The Roser et al (2016) study, not included in the *meta*-analysis, also showed no effect for complex attention.

In the *meta*-analysis there was no effect on learning and memory with the one-back memory task, or one card learning task with low certainty of evidence. However, in the Foerster et al. (2018) study, not included in the *meta*-analysis, statistically significant declines were found for figural memory with cordless phone calls and cumulative brain dose, but not with reported mobile phone calls. No effect was reported for verbal memory for any exposure metric.

No effect on executive function was found in the Stroop test in the *meta*-analysis, with very low certainty of evidence. For environmental exposure in children there was only one study that evaluated complex attention with no effect observed with low certainty evidence. None of the other domains have been evaluated for certainty of evidence in children.

In elderly people, for personal exposure, we found no effect on global cognitive function with only one study with very low certainty evidence. We found no effect in elderly people in the domain of complex attention with very low certainty. In the domain of memory we found no effect with very low certainty. Finally, we found no effect in the executive function domain in elderly people with very low certainty evidence. In none of the domains was an exposure −response relationship described.

Although the certainty of evidence in the domains across all studies ranged from very low to low, there appeared to be a consistent lack of evidence for an association between RF EMF exposure and cognitive function.

### 5.2. Limitations in the evidence

This systematic review investigated RF-EMF which includes all exposure sources within the 100 kHz to 300 GHz frequency range. However, the eligible studies in this review mainly addressed personal exposure in children primarily from mobile phones in the 300 MHz to 3 GHz range. Evidence was based on only 5 eligible studies, from 4 cohorts, with 4 studies in children. Only one study (Ng et al., 2012) investigated mobile phone use in elderly people. Only one study investigated environmental exposure encompassing various RF frequencies in children (Roser et al.,2016) and no studies investigated environmental exposure or occupational exposure in adults. No studies investigated the domains of language, perceptual motor ability and social cognition, in either children or adults.

The RoB and GRADE assessments identified various limitations in the available evidence. Two of the studies on children which were combined in a *meta*-analysis, Thomas et al (2010) and Bhatt et al (2017), had a high risk of detection bias because exposure to RF EMF was assessed indirectly via self-reported mobile phone use through questionnaires. Adding to the detection bias in these studies was the small exposure contrast noting that these studies analysed whether there was a change in exposure rather than the amount of change in exposure; however the exposure level was different in the two studies with the Thomas et al study having a median number of calls of 8 at baseline and 10 at follow up, whereas for the Bhatt et al study the median was 2 at baseline and 2.5 at follow up; noting that the percentage change in the median number of calls from baseline to follow up was the same in both studies i. e. 25 % increase. Further, the change analysis in these two studies makes temporality difficult to establish. Effects on executive function were inconsistent in these studies, but we were unable to explore potential reasons for inconsistency because there were only two studies. The other two studies on children, by Roser et al (2016) and Foerster et al (2018), which were similar, provided more valid assessments of exposure by also including a calculation on the brain dose of RF EMF. The brain dose calculation used propagation modelling, personal measurements, exposure questionnaires and mobile phone operator records to calculate both near-field and far field RF EMF exposures. The only other study on elderly people by Ng et al. (2012) had a high risk of attrition/exclusion bias, detection bias and imprecision for all domains investigated. In

**Table 3**
GRADE evidence profile.

| Certainty assessment | | | | | | | | | Summary of findings | | | Certainty | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Participants | Effect | | | |
| No of studies | Design | Initial rating | Risk of bias | Inconsistency | Indirectness | Imprecision | Publication bias | Upgrading Domains | No of participants | Relative (95 % CI) | Absolute (95 % CI) | | |
| Effects of personal exposure on global functioning in children | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | No studies | |
| Effects of personal exposure on complex attention in children (a positive MD indicates better complex attention)[1], [2] | | | | | | | | | | | | | |
| 3 | Cohort | Moderate | Serious (−1)[3] | Not serious | Not serious | Not serious | Undetected | No upgrading | 905 | | MD 0.02 (−0.04 to 0.08) | Low certainty | Two studies included in the *meta*-analysis (n = 615). Third study (n = 290) similar results. |
| Effects of personal exposure on executive function in children (a positive MD indicates better executive function)[4] | | | | | | | | | | | | | |
| 2 | Cohort | Moderate | Serious (−1)[3] | Serious (−1)[5] | Not serious | Not serious | Undetected | No upgrading | 612 | | SMD 0.02 (−0.01 to 0.04) | Very low certainty | |
| Effects of personal exposure on learning and memory in children (a positive MD indicates better learning and memory)[6] | | | | | | | | | | | | | |
| 3 | Cohort | Moderate | Serious (−1)[3] | Not serious | Not serious | Not serious | Undetected | No upgrading | 1285 | | MD −0.03 (−0.07 to 0.02) | Low certainty | Two studies included in the *meta*-analysis (n = 615). Third study (n = 670) similar results. |
| Effects of environmental exposure on global functioning in children | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | No studies | |
| Effects of environmental exposure on complex attention in children (a positive SMD indicates better complex attention) | | | | | | | | | | | | | |
| 1 | Cohort | Moderate | Not serious | Not serious | Not serious | Serious (−1)[7] | Undetected | No upgrading | 79 | | SMD −0.09 (−0.76 to 0.57) | Low certainty | |
| Effects of personal exposure on decline in global cognitive functioning in adults and elderly people | | | | | | | | | | | | | |
| 1 | Cohort | Moderate | Serious (−1)[8] | Not serious | Not serious | Serious (−1)[7] | Undetected | No upgrading | 649 | OR 0.81 (0.42 to 1.58)[9] | | Very low certainty | |
| Effects of personal exposure on decline in complex attention in adults and elderly people | | | | | | | | | | | | | |
| 1 | Cohort | Moderate | Serious (−1)[8] | Not serious | Not serious | Serious (−1)[7] | Undetected | No upgrading | 159 | OR 0.67 (0.27 to 1.68)[9] | | Very low certainty | |
| Effects of personal exposure on decline in executive function in adults and elderly people | | | | | | | | | | | | | |
| 1 | Cohort | Moderate | Serious (−1)[8] | Not serious | Not serious | Serious (−1)[7] | Undetected | No upgrading | 146 | OR 1.07 (0.37 to 3.05)[9] | | Very low certainty | |
| Effects of personal exposure on decline in learning and memory in adults and elderly people | | | | | | | | | | | | | |
| 1 | Cohort | Moderate | Serious (−1)[8] | Not serious | Not serious | Serious (−1)[7] | Undetected | No upgrading | 159 | OR 0.75 (0.29 to 1.99)[9] | | Very low certainty | |
| Effects of environmental exposure on global cognitive functioning in adults and elderly people | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | No studies | |
| Effects of occupational exposure on global cognitive functioning in adult workers | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | No studies | |

[1] For the domains, we included only the domains that were evaluated in studies. Other domains of cognitive function that are not in the table were not studied.
[2] Result shown is for accuracy on the detection task. Similarly, small effects were observed for the three other measures of complex attention with low certainty evidence.
[3] Probably high risk of bias in the two studies included in the *meta*-analysis; downgraded with one level.
[4] Result shown is for the Stroop test (B-A/A). A similar small effect was reported for the Stroop test (D-C/C) with low certainty evidence.
[5] I-square 88%, downgraded with one level.
[6] Result shown is for accuracy on the one-back memory test. Similarly, small effects were observed for the three other measures of learning and memory with low certainty evidence.
[7] 95% CI compatible with a considerable decrease and a considerable increase in test score with higher exposure; downgraded with one level.
[8] Probably high risk of bias in one study; downgraded with one level.
[9] OR for the largest exposure contrast never vs > 7 calls per week.

addition, the small number of participants contributing to most analyses reported by Ng et al led to imprecision that reduced confidence in the evidence because the confidence intervals were compatible with both harm (decline in cognition) and benefit for the various cognitive function domains.

Only the Ng et al (2012) study reported global cognitive function as well as domain specific cognitive function. Neuroscientists have long known that specific sites in the brain are involved with the specific domains. For example, the hippocampus provides temporary storage for new information whereas other areas handle long-term memory and executive function (Reisberg, 2013). However, given the exposure assessment was not specific to the brain regions of the specific domains, interpretation of results at the region level is not deemed informative with the current studies.

### 5.3. Limitations in the review process

In this review there were several potential limitations mainly arising from limitation in the evidence base. Unlike previous systematic literature reviews (Ishihara et al., 2020), we did not include cross-sectional or ecological studies. While this reduced the number of eligible studies, inclusion of cross-sectional studies would not increase the certainty of the evidence. A number of cross-sectional studies have examined the association between RF-EMF exposure and cognition; these have mainly assessed mobile phone use (see excluded studies in **Supplemental File S2**). Narrative reviews of these cross-sectional studies report inconsistent associations, with some included studies reporting improvement in cognitive function (Ishihara et al., 2020; ICNIRP, 2020; ARPANSA, 2014). This highlights the problems with cross-sectional studies where the simultaneous assessment of exposure and outcome makes a causal effect difficult to establish. Further, any reported effects (whether improvement or decline in cognition) could be due to behavioural factors rather than exposure to RF-EMF and the cross-sectional studies did not control for potential confounding factors.

Our review considered the effect of long-term exposure to RF-EMF on cognition and did not include possible acute effects. Acute effects on cognitive function have been investigated by a number of experimental studies, and a systematic review is in progress evaluating the effects of RF-EMF on cognition in experimental studies (Pophof et al.,2021).

Other eligibility criteria which impacted on the number of studies that were included in our review were the exclusion of studies using self-reported distance of antenna exposure or calculated distance to mobile phone base stations as exposure metrics and the specification of cognitive domains based on validated tests.

Assessment of the exposure was a limitation that has been reported in previous reviews of RF-EMF and cognitive function (Ishihara et al.,2020). These limitations included the high reliance upon self-reported exposure in studies. To-date nearly all studies (including those in this review) have reported this factor as a limitation in this field of research. However, the HERMES studies that used objective mobile phone operator data had similar results to the self-reported data (Roser et al., 2016; Foerster et al., 2018).

Training effects of computer usage in cognition testing in four of the five studies in this review were also a limitation that may have caused a bias towards a null finding. In a commentary on training and cognitive function testing, Wesnes and Pincock (2002) observed:"Practice effects on cognitive tests are not a minor nuisance but a major potential problem that must be overcome by appropriate prestudy training." However, uncertainty analysis in the Bhatt study (2017) indicated that results could be biased in either direction (Brzozek et al., 2019).

The study data collection periods may have introduced limitations in this review. Exposures in the Thomas et al (2010) and Ng et al (2012) studies were sampled prior to the introduction of smart phones with only 2G and 3G technology exposure. This is in contrast to the remaining included studies where 4G technology and behaviours in use would have been very different. Behaviours in texting/gaming/social media and talking would have likely affected exposures. Recently, van Wel et al (2021) also described the different behaviours of use of phones according to age in their survey. Further, for the time period assessed in this review, cordless phone exposures may have added to exposure misclassification (where not assessed), especially for all technologies after 2G (van Wel et al., 2021).

In all included studies the effects of RF-EMF from mobile phones cannot be separated from the effects of mobile phone use behaviours e.g. texting/gaming/social media, and the effects these behaviours have on cognition. Findings by Brzozek et al (2018) and van Wel et al (2021) clearly show that behaviours of use can change within subjects, between age groups or country of origin. In particular, non-call activities show high variability and a focus on specific cognitive effects due to the behaviour of users is required.

Limitations were also encountered in domain specific cognitive function in studies which meant only two could be included in the *meta*-analysis. We found that the memory and learning tests were reported as % accuracy and response time in milliseconds in the CogHealth (Cogstate, Melbourne, 2005) test battery used in the Thomas et al. (2010) and Bhatt et al. (2017) studies. These were not directly comparable with the figural and verbal memory subtests of the Intelligenz- Struktur- Test (IST) (Liepmann et al.,2007) used in the Foerster et al. (2018) study. Similarly, the complex attention tests in CogHealth used in the Thomas and Bhatt studies were not comparable to the FAKT-II test battery used in the Roser study. Previous reviews (Ishihara et al., 2020), recognised the lack of comparability across different studies and, for this reason, the authors chose to limit their synthesis to methods of vote counting (including those based on statistical significance, which are widely regarded as having serious limitations and can lead to the wrong conclusion) (McKenzie and Brennan, 2023; Hedges and Vevea, 1998).

### 5.4. Implications for practice and policy

We found low to very low certainty evidence that suggests that RF EMF exposure from mobile phone use may not have a major long-term (months to a few years) effect on complex attention, executive function and learning and memory among children. However, the evidence is limited to a few studies in specific settings and is generally very low to low certainty. There is no evidence from cohort or case-control studies about effects on other cognitive domains, including language, perceptual motor ability and social cognition as these domains were not assessed in any of the included studies. The exposure from mobile phones evaluated in the included studies is presumed to have been below the exposure limits recommended by international guidelines (ICNIRP, 2020; Ramirez-Vazquez et al., 2023), given that they are used to regulate exposure levels in the countries where the studies were conducted. It is important to note, however, that the purpose of this systematic review was not to investigate the adequacy of the ICNIRP exposure limits.

### 5.5. Implications for research

To improve our understanding of long term RF-EMF exposure and cognition, cohort observational studies that address important gaps in the evidence and the methodological limitations of existing studies are needed. There are important gaps in existing evidence in terms of the populations, exposures and outcomes assessed. No study investigated environmental exposure and cognition in adults or the elderly. Furthermore, no studies reported on effects of occupational exposure and cognition, despite many occupational studies having reported on RF-EMF effects on other health outcomes such as cancer (ARPANSA, 2014). This is an important field of investigation for future studies.

To enable synthesis of evidence, and ensure relevance of findings, researchers need to reach consensus about uniform methods of exposure and outcome assessment. The exposure assessment could be improved in future studies in the following ways: Firstly, exposure assessment needs

to be at an individual level over a sufficiently long duration. The RF-EMF brain dose model described by Roser et al. (2015) and subsequently used in the Foerster et al (2018) study, has been further developed by van Wel et al (2021), and should be considered in future studies; remembering also that these dose estimations still require input data on use which, in most studies, still comes from questionnaires (and sometimes but not always with external validation). Although a robust exposure metric, the use of "number of calls per week" in the Thomas et al (2010) and the Bhatt et al (2017) may be considered an inferior metric to use of the "brain dose model" (van Wel et al.,2021), but the brain dose model may also be improved. Van Wel et al (2021) note high uncertainty in their model outputs and this uncertainty must be addressed. Brzozek et al (2019) present Monte Carlo simulation as an additional approach to analysis by addressing uncertainty in model inputs using error probability distributions, rather than point-source data. Self-reported exposures have known limitations and future studies need to incorporate exposure assessment metrics that involve more objective and unbiased estimates (Vrijheid et al.,2009). In recent years with the introduction of 5G (5th generation mobile network), coupled with the phasing out of 2G, 3G, fixed line and DECT (digitally enhanced communication technology) as well as the pattern of mobile phone use (i.e. using apps rather than making phone calls), the exposure profile of people may change. This will further necessitate the need for modelling of energy deposition and duration of exposure for dose estimation.

There is an urgent need for consensus on the cognitive domains that should be measured in future studies and a core set of cognitive function tests for evaluation of each domain. The five included studies originated from three countries using cognitive test batteries developed in the local language of those countries. The absence of tools validated in different languages has been a barrier to identification of a universal battery of tests, which was demonstrated in the current review. The Stroop colour word test should be considered for executive function comparisons in all future studies, as this is a well validated test that is easy to administer to large numbers of participants and the results can be easily interpreted across cultural and ethnic groups (Geukes et al., 2015). Only the Ng et al (2012) study reported an assessment of global cognitive function, which none of the studies included on children reported.

**Other information**

**Registration and protocol**.

The protocol for this review was registered in Prospero reg no CRD42021257548 and published in Environment International 2022.

**Changes from protocol**.

Information sources and search strategy: In response to peer review comments, the search of EMF-Portal was amended to include the topic 'Epidemiological Studies'. We identified and screened 18 unique records, none of which met the inclusion criteria. The PRISMA flow diagram reflects the results of the amended search.

We specified the four key-items for reporting the tiers of study quality which included selection/attrition biases, and exposure/outcome detection biases. We further described that tier-1 comprised studies with definitely or probably low risk of bias for all key-items and most of other items; tier-3 included studies with definitely or probably high risk of bias for all key-items and most of other items; and studies that did not meet the criteria for tier-1 or tier-3 were classified as tier-2.

We originally conducted a *meta*-analysis of similar studies with random effects models. However, because only two studies were available from the same research group we followed the recommendation of Bender et al (2018) and conducted a fixed effects *meta*-analysis following peer-review. The forest plots of the original random-effects *meta*-analysis are available in **Supplemental File S6**.

Effect measures: We used Cohen's guiding rules for interpreting MDs or SMDs where −0.2 to 0.2 represents a trivial effect ('little to no difference'), 0.2 a small effect, 0.5 a moderate effect, and 0.8 a large effect (Schuneman et al., 2019). For odds ratios, we considered whether relative effects indicated an important effect (an OR $> 1.25$ or $< 0.80$) and confirmed this interpretation by calculating the absolute risk difference (using an ARD of 5 % as an important effect). We confirmed our interpretation of odds ratio reported by Ng et al (global cognitive function, executive function, complex attention, learning and memory) by calculating absolute effects using the corresponding baseline risks reported in Ng et al. and comparing these to our threshold for an important effect of an ARD of 5 %.

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**Declaration of Competing Interest**.

GB, SB, HK, JK and BZ declare they have no competing interests. MA declares that he holds a small parcel of Telstra shares. KK, CB and MS as part of their employment are involved in the provision of advice to the Australian Commonwealth Government, Australian States and Territories and the general public on the risks and health effects of exposure to ionising and non-ionising radiation. KK is also a member of the International Commission on Non-Ionizing Radiation Protection where he contributes in the development and dissemination of science-based advice on limiting exposure to non-ionizing radiation.

No member of the review team was involved in screening or extracting data from a study in which he or she was an author.

## CRediT authorship contribution statement

**Geza Benke:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition. **Michael J. Abramson:** Writing – review & editing, Writing – original draft, Methodology. **Chris Brzozek:** Writing – review & editing, Writing – original draft. **Steve McDonald:** Writing – review & editing, Writing – original draft, Methodology. **Helen Kelsall:** Writing – review & editing, Writing – original draft. **Masoumeh Sanagou:** Writing – original draft, Methodology, Formal analysis. **Berihun M. Zeleke:** Writing – review & editing. **Jordy Kaufman:** Writing – review & editing. **Sue Brennan:** Writing – review & editing, Writing – original draft, Methodology. **Jos Verbeek:** Writing – review & editing, Writing – original draft, Methodology. **Ken Karipidis:** Writing – review & editing, Writing – original draft, Supervision, Methodology.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Dr Geza Benke reports financial support was provided by World Health Organization. MA declares that he holds a small parcel of Telstra shares. KK, CB and MS as part of their employment are involved in the provision of advice to the Australian Commonwealth Government, Australian States and Territories and the general public on the risks and health effects of exposure to ionising and non-ionising radiation. KK is also a member of the International Commission on Non-Ionizing Radiation Protection where he contributes in the development and dissemination of science-based advice on limiting exposure to non-ionizing radiation. No member of the review team was involved in screening or extracting data from a study in which he or she was an author].

## Data availability

Data will be made available on request.

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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.2024.108779.

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