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Systematic reviews and *meta*-analyses for the WHO assessment of health effects of exposure to radiofrequency electromagnetic fields, an introduction

1. Introduction

We, the editors (SI, JFD, SD, NR, PW) and organizers (JV, EvD, HZ) of this special issue of *Environment International* on the World Health Organization's (WHO) assessment of the health effects of exposure to radiofrequency (RF) electromagnetic fields (EMF), are pleased to present this collection of systematic reviews of the effects of RF EMF. This issue represents the culmination of four years of meticulous, collaborative work by more than 80 scientific experts from around the world. We extend our sincere congratulations to the authors of the reviews and commend their dedication to producing reviews of such high scientific quality.

This Special Issue includes nine protocols and subsequent twelve systematic reviews, all designed to support the human health risk assessment of RF-EMF exposure. In this editorial, we summarize the processes used to commission and develop the systematic reviews, describe the methodological tools employed, and summarise the key findings. We also reflect on the successes and challenges encountered throughout this ambitious undertaking.

Collectively, these systematic reviews offer a robust model for global health risk assessments, contributing to the development of evidence-based norms, standards, and research priorities. This project stands as one of the most comprehensive evaluations of environmental health evidence to date – an effort from which we continue to learn how to best approach this task (Jarosińska et al. 2018; Pega et al. 2021; Pérez Velasco and Jarosińska 2022).

2. Health risk assessment of electromagnetic fields

Exposure to RF EMF (frequencies ranging from 100 kHz to 300 GHz) is widespread today (Ramirez-Vazquez et al. 2023), primarily due to wireless telecommunications, including mobile phones, as well as various industrial and medical applications. As RF EMF exposure affects virtually everyone and is constantly evolving, it is important to review the evidence regarding potential health risks associated with RF EMF exposure.

The established health effects from exposure to RF EMF include those resulting from excitation of sensory cells or other nerve cells at lower frequencies in the RF range, and from increased tissue temperature in the upper frequency range. Current exposure limits (D'Andrea et al. 2007; ICNIRP 2020) are set to ensure that RF EMF exposure will not raise core body temperature by more than one degree Celsius. Although no other mechanisms beyond nerve cell excitation and thermal effect are known to pose health risks (Sheppard et al. 2008), the possibility remains that other, as yet unknown, biophysical mechanisms could exist and potentially lead to health effects.

WHO has a long-standing history in reviewing the findings of research on the health risks of human exposure to EMF through its Environmental Health Criteria (EHC) Monograph series (World Health Organization 1993; 2006; 2007; 2010). This series includes comprehensive reviews commissioned to groups of independent scientists addressing the potential health effects of exposure to static, extremely low frequency (ELF), and radiofrequency (RF) fields. These assessments are crucial for informing public health policies and ensuring safe levels of exposure to EMF. The EHC series on EMF continues to be an essential reference point for many national/ regional guidelines for protecting population health and a resource for understanding and managing the health impacts of electromagnetic fields.

The last EHC Monograph on RF fields was published in 1993 (World Health Organization 1993) and is currently being updated to reflect new scientific evidence. The updated Monograph will complement those on static fields (2006) and ELF fields (2007), providing a comprehensive assessment of the health risks associated with RF field exposure. The development of this Monograph on RF field exposure adheres to the strict WHO guidelines (World Health Organization 2014). The risk assessment in this new Monograph edition will be based on syntheses of the latest evidence relating to exposure to EMF exposure and health outcomes. This includes the systematic reviews in this special issue which applied the latest scientific review methodologies such as those described in the COSTER recommendations (Whaley et al. 2020).

3. The approach

The approach to developing the overall scientific basis for the updated EHC Monograph on RF Field exposure had three sequential parts: a scoping review, a prioritisation of outcomes, and the set of systematic reviews presented in this special issue. As part of the WHO's RF EMF health risk assessment process, the evidence from the scoping review and the systematic reviews in this special issue will be used to draw conclusions about the risks associated with RF EMF exposure from various streams, including human observational and experimental studies, animal, and in-vitro studies. This is currently being conducted by a task group distinct from both the scoping review team and the systematic review teams.

3.1. Scoping review

The effects of RF EMF on health have been studied extensively, yet

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few reviews exist that try to systematically synthesize the overall evidence base. To prepare for the EHC Monograph on RF EMF, WHO involved a core group of dedicated scientists in 2012 who, together with a larger group of experts, examined the research activity in this field and carefully evaluated all studied health outcomes related to RF EMF exposure. This scoping review identified several thousand articles assessing one or more health effects of RF EMF and will be published soon as part of the underpinning of the updated EHC Monograph. However, drawing robust conclusions from a scoping review alone is challenging. Therefore, systematic reviews were necessary to determine both the magnitude and certainty of the most important effects studied.

3.2. Prioritization of health outcomes

Focusing on the most important outcomes enables more efficient use of resources and supports the development of a manageable and targeted assessment. To achieve this, a prioritization exercise was conducted by WHO to identify the most critical outcomes. A survey was distributed to over 300 RF EMF experts to determine which health outcomes should be prioritized for systematic review. From an initial list of 34 potential outcomes, the survey identified six key areas: heat-related health outcomes, cancer, effects on male and female fertility, cognitive impairment, subjective symptoms, and oxidative stress as the most critical health topics related to RF EMF exposure. The survey and its results are reported in (Verbeek et al. 2021). The priority topics resulting from the survey formed the input for the systematic review part of the project.

3.3. Systematic reviews

3.3.1. Process

The WHO team then developed questions on all priority topics in the PECOS format. This format defines the Population (P), Exposure (E), Comparator (C), Outcomes (O), and Study design of interest. This framework ensures a consistent and focused approach for the systematic reviews (Morgan et al. 2018) and enables an evidence base for drawing robust conclusions. Based on these PECOS questions, WHO issued an open call for research teams interested in conducting systematic reviews on the effects of RF EMF exposure.

All systematic review team members were required to disclose any potential conflicts of interest – including financial interests and any paid or unpaid roles in which they represented or advocated for positions related to the subject matter of the work. These disclosures were thoroughly assessed and managed by WHO. For more information on the procedure see https://www.who.int/about/ethics/declaration-of-interests.

For each prioritized topic, WHO commissioned systematic reviews separately for human observational, human experimental and animal studies. WHO selected international teams based on a balanced combination of subject-matter expertise and systematic review methodology skills. Each team was tasked with the elaboration of a detailed protocol and subsequently conducting systematic reviews for their assigned outcomes.

3.3.2. Methods

WHO aimed to ensure that the methods used in different reviews were as similar as possible to guarantee comparable conclusions across reviews. The guidance in the WHO's Guideline Development Handbook was followed as closely as possible (World Health Organization 2014) together with the more specific guidance for systematic reviews of the effects of exposure (Morgan et al. 2018; Whaley et al. 2020). WHO, together with the systematic review teams, selected the OHAT handbook for systematic reviews (Office of Health Assessment and Translation (OHAT) 2019) as the most comprehensive source suitable for reviews of RF EMF exposure and the wide array of study designs, including animal and cell studies. The handbook provides detailed guidance for adapting risk of bias assessment to different study designs while maintaining the same structure and domains. It also offers guidance for applying the GRADE approach (Guyatt et al. 2008) to certainty assessment for exposure questions. In addition, WHO and the systematic review teams included a specific method for conducting *meta*-analyses of dose–response data (Orsini et al. 2022) where needed and possible.

To ensure consistency and high-quality reporting of the systematic reviews, WHO relied on the publication process of Environment International in accordance with the journal's rigorous editorial standards (Whaley and Roth 2022)). As required by the journal, each review team first developed a detailed protocol, which was evaluated for compliance with rigorous systematic review standards of Environment International. The protocols underwent peer review and were subsequently published as part of this special issue. The systematic review teams then developed the systematic reviews which were evaluated for adherence to their respective protocols, transparency in reporting, and the appropriateness of result interpretation by the editorial team and the peer reviewers. For one of the review topics – heat-related effects – a systematic review was not completed. The protocol did not pass peer review process in time and proceeding with it would have significantly delayed the overall project. As a result, this systematic review was decommissioned.

3.3.3. Results

The systematic reviews report evidence for the effects of RF EMF on all important health outcomes but the number of studies finally included for each outcome varied significantly, ranging from five studies on cognitive function in human observational studies (Benke et al. 2024) to 215 studies on fertility in animal experimental studies (Cordelli et al. 2023; Cordelli et al. 2024).

The systematic reviews of human observational studies on cancer found moderate-certainty evidence of no or only a small effect for several important cancer types, such as glioma and lymphoma (Fig. 1), based on 74 studies/databases (Karipidis et al. 2024; Karipidis et al. 2025). Only for thyroid cancer and oral cavity/pharynx cancer the evidence was respectively low and very low. The review of cancer in experimental animals (Mevissen et al. 2025) identified 10 long-term bioassays and dozens of other studies. Based on only one or two of these studies, the authors concluded that there was high- to moderate-certainty evidence of an effect of RF EMF on five cancer types in animals.

The review of fertility outcomes in experimental animals yielded the most varied results. It found high-certainty evidence of no or only a small effect on litter size, but also high-certainty evidence of a large adverse effect on male fertility (Cordelli et al. 2023; Cordelli et al. 2024). (Fig. 2) Unfortunately, there were only few human observational studies on fertility that produced only very low-certainty evidence (Johnson et al. 2024; Pw Kenny et al. 2024).

For cognition, human experimental studies provided consistent moderate- to high-certainty evidence of no or only a small effect across several domains of cognitive performance (Pophof et al. 2024). (Fig. 3) However, the corresponding human observational review (Benke et al. 2024) included only a few studies with results that were assessed as very low certainty.

Regarding symptoms, human experimental studies (Bosch-Capblanch et al. 2022) showed moderate-certainty evidence of no or a small effect of RF EMF exposure. Yet again, the limited number of human observational studies resulted in very low certainty evidence (Roosli et al. 2024).(Fig. 4).

Finally, the review of effects of RF EMF on oxidative stress (Meyer et al. 2024) found highly variable results, ranging from large increases to large decreases in oxidative markers across all outcomes, even within one homogenous PECO. The certainty of evidence was rated very low largely due to a high risk of bias in the included studies. This was particularly evident in the exposure domain, where many experimental studies still relied on mobile phones to generate exposure – a method prone to bias if not carefully controlled (Kuster and Schönborn 2000).

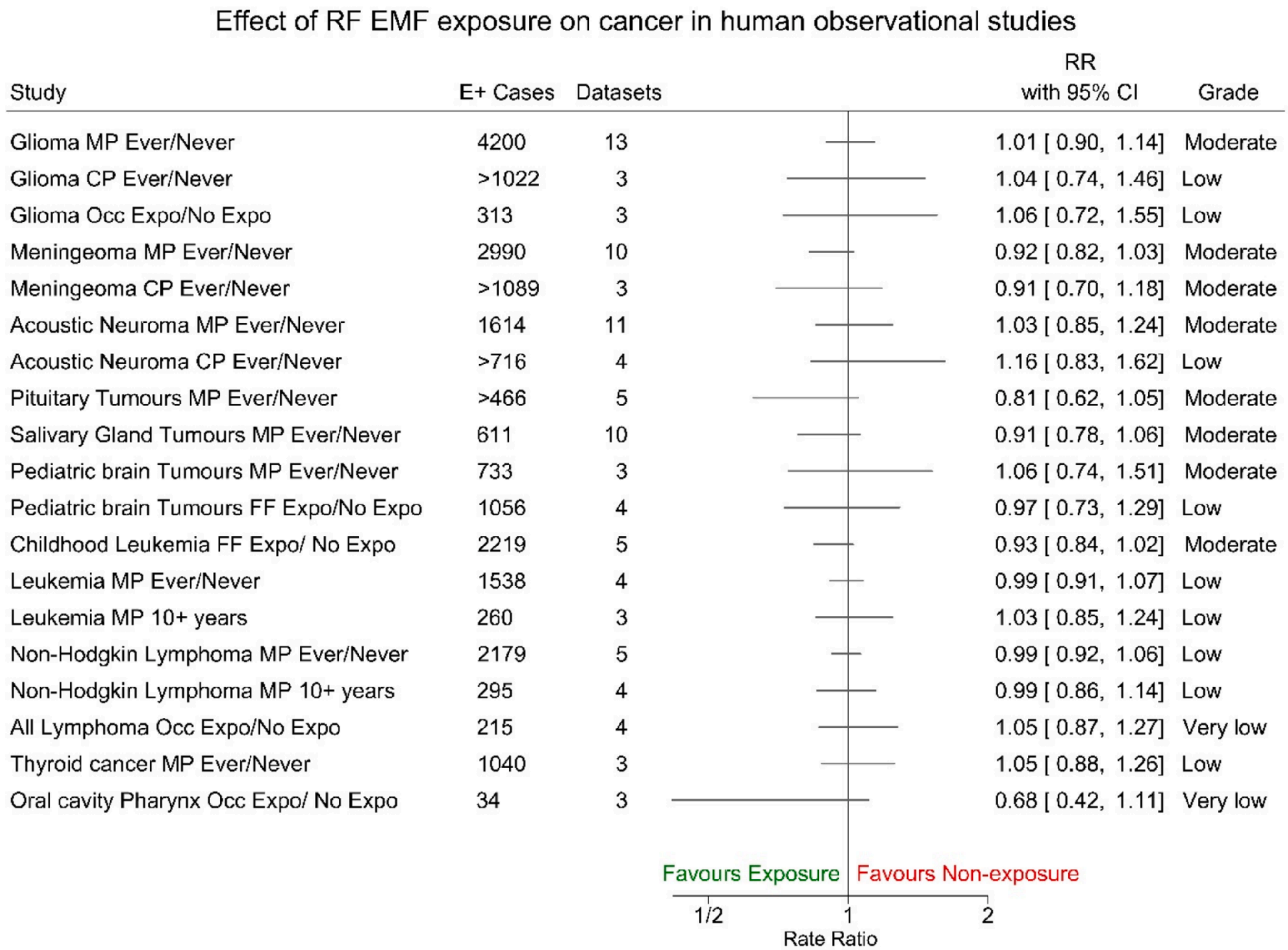

Fig. 1. Results from systematic review of effects of RF EMF on cancer in human observational studies as reported in the summary of findings table. MP = mobile phone, CC= Cordless Phone, FF = Far Field, Occ= Occupational Exposure, Grade = certainty of the evidence.

4. Achievements, challenges, and lessons learnt

We successfully harmonized the methodology across the series of systematic reviews, resulting in consistent and comparable approaches across almost all reviews. The overall quality of the syntheses and reporting was further enhanced by the supportive editorial process provided by the journal at several stages of the work. This included checking requirements of PRISMA and protocol adherence, direct contact via phone and email between authors, editors and method experts and high-quality peer-review. It would have been harder to achieve the clear and robust reports at hand currently without these elements. To support this effort, the journal invested significant resources – including topic and methodological expertise as well as administrative support – into the editorial process for this series.

Each protocol and systematic review underwent an initial triage by the Special Issue editors, who assessed compliance with best practices in systematic review methodology, the general validity of the approach, and potential issues that could hinder the peer-review process. Manuscripts were then handed to Guest Editors with specific topic or technical expertise to manage the peer-review process, which involved up to five reviewers per review.

The formal prior publication of protocols allowed peers in the field to comment on the planned methods before data was collected. This enabled review teams to refine their methods more effectively than when data had already been collected and analyzed. Having a published record of planned methods also strengthened the evaluation of the final reviews, as it discourages post hoc changes and ensures that any necessary modifications are transparent and open to discussion.

We commissioned systematic reviews for specific health topics and study designs only. This approach allowed for focused and comprehensible syntheses of the evidence but also limited the ability to draw overall conclusions on the broader health topic. For example, separate reviews were conducted for human and animal evidence for fertility and for cancer. This led to clear conclusions of the individual reviews but, as is particularly clear in cases where the animal evidence appears to contradict the human evidence, will necessitate another step of integration of the conclusions of the reviews in an overall conclusion “what this evidence means for human health”. This is the next step still to be conducted by a dedicated WHO Task Group.

The OHAT handbook proved especially valuable for this project which included various evidence streams, including cell studies, animal studies, human observational studies, and human experimental studies. Although advanced risk-of-bias instruments exist for certain designs, such as cohort studies of exposure (Higgins et al. 2024), they cover only a subset of the study designs commonly used in environmental health research.

The initial scoping review played a key role in identifying and refining relevant systematic review questions, helping to ensure that the commissioned reviews addressed the most critical and policy-relevant topics.

We have learned that systematic review teams benefit greatly from having members with expertise in both exposure and outcome

Effects of RF EMF on Fertility Outcomes in Human Animal and Human In-Vitro Studies

Study	Participants	Studies/Datasets	SMD with 95% CI	Grade
Female, human observational, pregnancy				
Congenital malformations FF DR	834	2	-0.19 [-0.47, 0.09]	very low
Low birth weight FF	1 081	3	-0.57 [-1.29, 0.15]	very low
Low birth weight MP	153 929	4	-0.07 [-0.17, 0.03]	very low
Miscarriage FF DR	952	2	-0.01 [-0.05, 0.03]	very low
Miscarriage FF	4 932	5	-0.03 [-0.09, 0.03]	very low
Preterm birth FF	1093	3	-0.10 [-0.48, 0.28]	very low
Preterm birth MP	153 929	4	-0.07 [-0.16, 0.02]	very low
Small for gestational age MP	153 027	2	-0.07 [-0.12, -0.02]	very low
Female, animal, fecundity				
Dead foetuses	4611	21	-0.34 [-0.55, -0.13]	low
Litter size	1908	25	-0.03 [-0.13, 0.08]	High
Female, animal, pregancy				
Motor and sensory function	60	2	-0.66 [-1.18, -0.14]	Very low
Fetal length	707	14	-0.45 [-0.82, -0.07]	Low
Fetal malformations	925	13	-0.45 [-0.89, -0.00]	Low
Fetal weight	2680	49	-0.35 [-0.53, -0.17]	Moderate
Litter with malformations	4192	28	-0.65 [-0.94, -0.35]	Very low
Sex ratio	2667	13	-0.04 [-0.13, 0.06]	Low
Female, animal, pregnancy delayed effects				
Brain pathology	1245	12	-0.10 [-0.29, 0.09]	Moderate
Female infertility	152	4	-0.08 [-0.55, 0.39]	Low
Learning memory	32	2	-0.54 [-1.25, 0.16]	Very low
Motor activity	120	4	-0.79 [-1.38, -0.21]	Very low
Male, animal, fertility				
Litter size	463	16	-0.04 [-0.23, 0.15]	Moderate
Litter size-EMP	100	5	0.38 [-0.15, 0.91]	Low
Non-pregnant females over paired females	1187	19	-0.29 [-0.55, -0.03]	High
Non-pregnant females over paired females-EMP	50	5	0.06 [-0.41, 0.53]	Low
Rate of infertile males	144	4	-0.18 [-0.99, 0.62]	Very low
Male, human in-vitro, semen				
Sperm dna alterations	410	13	-0.17 [-0.47, 0.13]	Very low
Sperm vitality	910	23	-0.26 [-0.45, -0.07]	Very low
Male, animal, semen				
Sperm count	1321	80	-0.74 [-0.98, -0.50]	Low
Sperm count-EMP	150	10	-0.23 [-0.56, 0.09]	Low
Sperm dna alterations	111	6	-1.92 [-2.78, -1.05]	Very low
Sperm morphology	1003	65	-0.56 [-0.83, -0.29]	Very low
Sperm morphology-EMP	150	10	-1.57 [-2.15, -1.00]	Very low
Sperm vitality	599	32	-1.51 [-2.07, -0.95]	Very low
Sperm vitality-EMP	80	2	-0.83 [-2.72, 1.06]	Very low
Male, animal, reproductive organ toxicity				
Testicular cell death	453	23	-1.18 [-1.82, -0.54]	Very low
Testicular cell death-EMP	50	5	-0.05 [-0.90, 0.80]	Very low
Testicular sperm production	607	36	-0.87 [-1.23, -0.51]	Very low
Testis epididymis weight	1228	55	-0.29 [-0.47, -0.10]	Very low
Testis epididymis weight-EMP	180	10	-0.16 [-0.45, 0.13]	Very low
Testis histomorphometry	335	24	-0.90 [-1.48, -0.31]	Very low
Testis histomorphometry-EMP	150	10	-0.66 [-0.99, -0.33]	Very low
Testis or epididymis histology	233	17	-1.43 [-2.10, -0.75]	Very low
Male, animal, hormonal				
Testosteron level	783	29	-0.87 [-1.30, -0.44]	Very low
Testosteron level-EMP	214	6	1.74 [-0.44, 3.92]	Very low

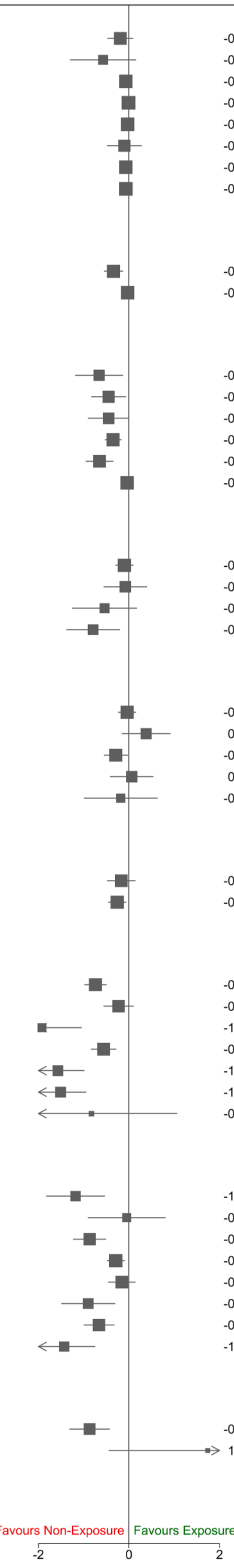

Fig. 2. Results from the systematic reviews on the effects of RF EMF on female fertility and male fertility in human observational and animal experimental studies as reported in the summary of findings tables. To make the results comparable, SMDs were converted so that all negative SMDs indicate an adverse effect, and RRs and ORs were converted to SMDs with the appropriate formula. The results for MDs were reanalyzed and are here reported as SMDs. EMP = pulsed electromagnetic fields. DR = dose–response.

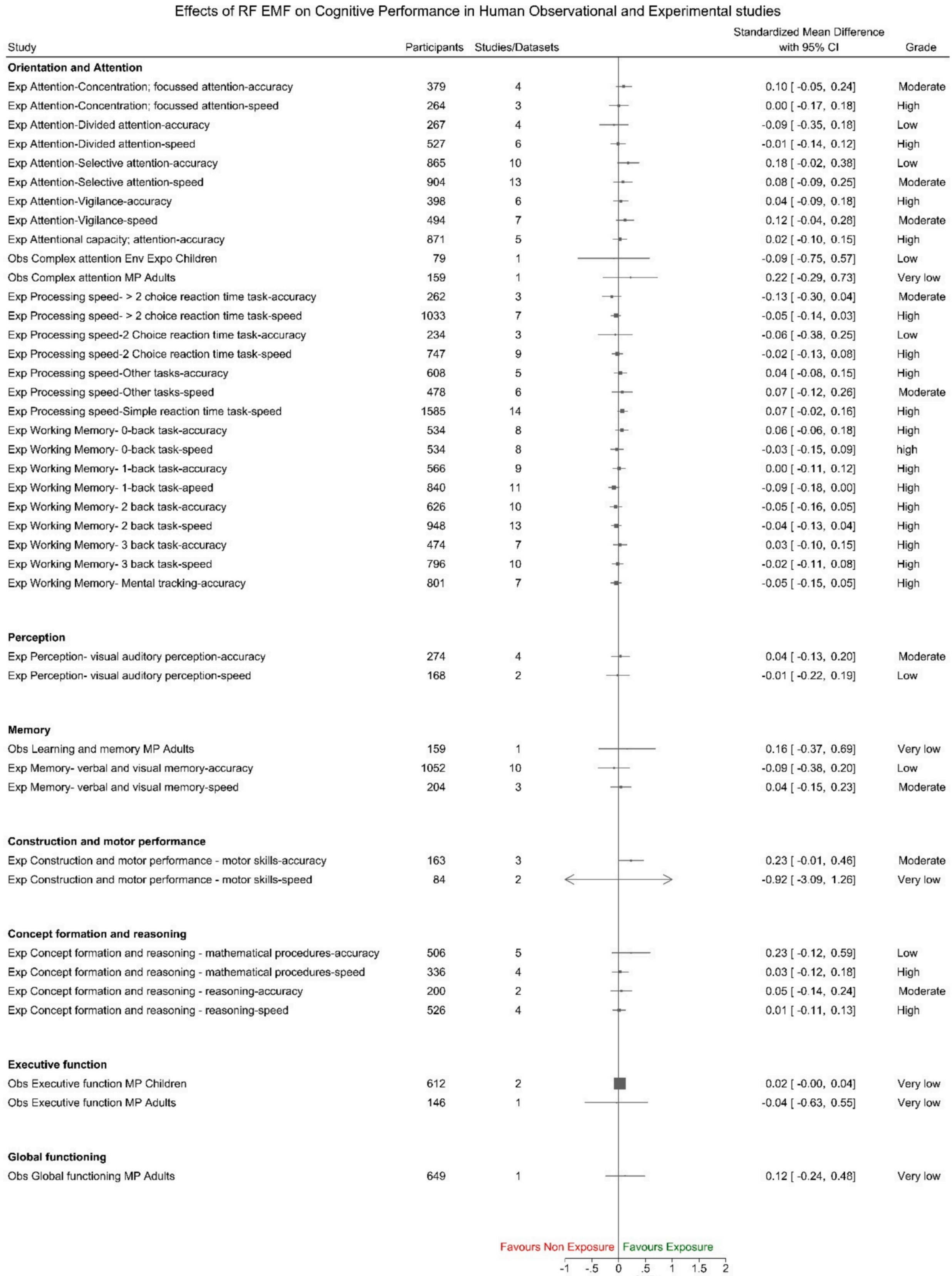

Fig. 3. Results of the systematic reviews of human observational (Obs) and human experimental studies (Exp) on the effects of RF EMF on cognition as reported in the summary of findings tables. To make the results comparable, SMDs were converted so that all negative SMDs indicate an adverse effect, and RRs and ORs were converted to SMDs with the appropriate formula. Two results expressed as MDs from the human observational studies could not be reanalyzed and are missing here. SMD = standardized mean difference.

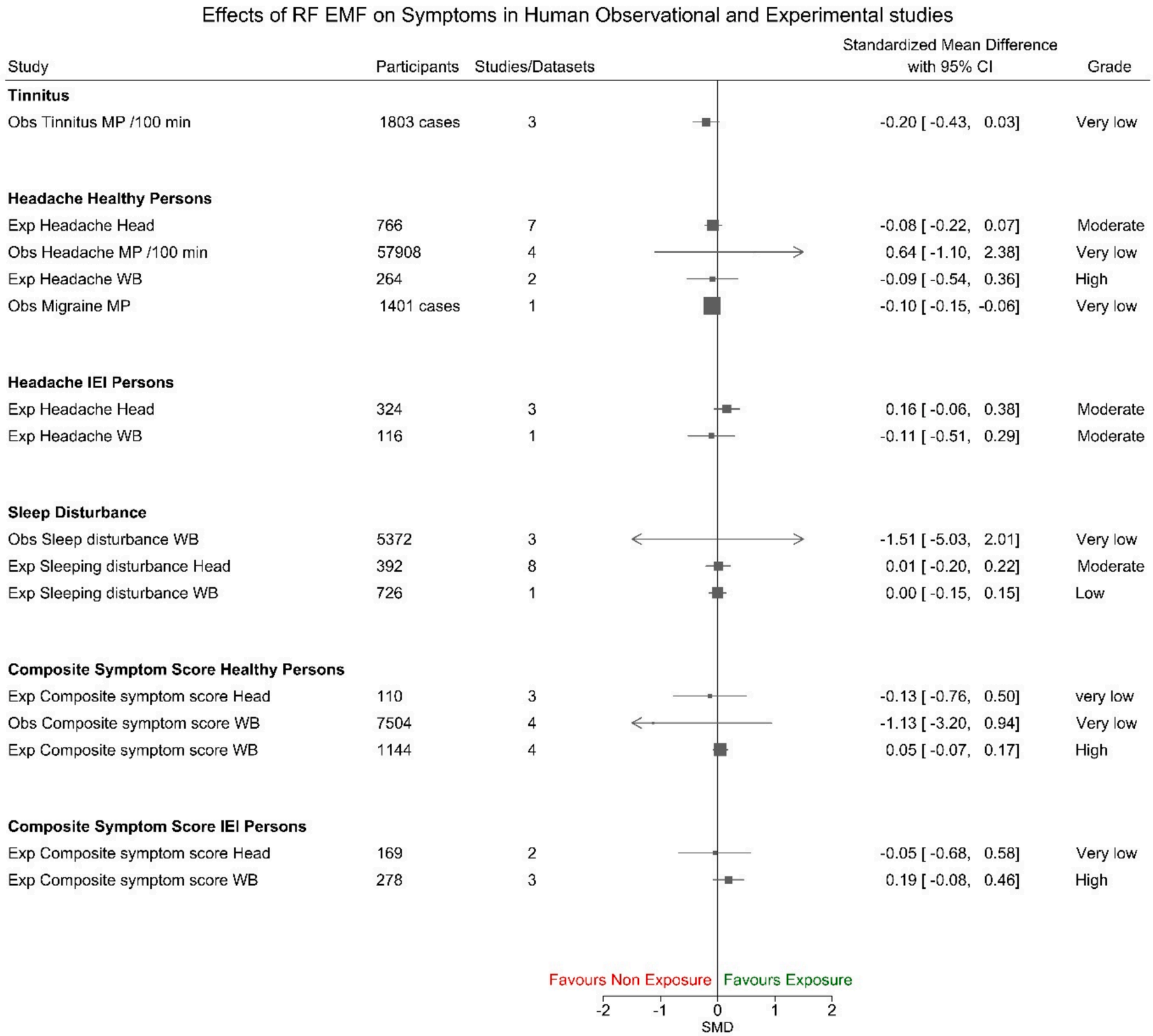

Fig. 4. Results of the systematic reviews of human observational (Obs) and human experimental studies (Exp) on the effects of RF EMF on symptoms as reported in the summary of findings tables. To make the results comparable, SMDs were converted so that all negative SMDs indicate an adverse effect, and RRs and ORs were converted to SMDs with the appropriate formula. Two results expressed as MDs from the human observational studies could not be reanalyzed and are missing here. SMD = standardized mean difference.

assessment. However, in the case of RF EMF, this dual expertise is rare, as exposure assessment requires a distinct set of skills, methods, and instruments that differ significantly from those used to evaluate biological or health outcomes. This underscores the importance of assembling teams with complementary expertise and fostering strong collaboration among members. Ensuring a well-functioning team is therefore essential – but challenging to assess and guarantee in advance.

Overall, this was a challenging project, involving over a hundred scientists from diverse fields, each bringing different perspectives and approaches to conducting systematic reviews. The timeline was ambitious, especially given the extensive volume of evidence that required careful and thorough analysis. Although the initial goal was to publish the reviews within one year of protocol publication, the publication of the protocols took on average 8 months, and the time from protocol publication to final review publication averaged two years and eight months. In hindsight, many review teams acknowledged that they had underestimated the scope and complexity of the work. The sheer volume of data necessitated meticulous analysis, which proved to be more time-consuming than initially anticipated.

The COVID-19 pandemic introduced additional, unforeseen challenges. Teams were unable to meet in person which added complexity to collaboration and coordination. Despite these obstacles, the teams remained committed to and largely succeeded in delivering comprehensive, high-quality systematic reviews.

One notable exception was the systematic review on the effects of RF EMF on cancer in experimental animals, which stood out due to its use of a different synthesis method. The authors concluded that there was an effect of RF EMF if two studies showed statistically significant results, disregarding null findings from other studies. This approach deviated from the protocol, which had indicated the use of relative risk as the primary synthesis method (Mevissen et al. 2025). Despite extensive discussions with editors and peer reviewers, the review ultimately concluded that there was high-certainty evidence of an effect on cancer. Whether this method proves valid – and whether alternative synthesis approaches would yield the same conclusion—remains to be seen.

Although the number of potential health outcomes was reduced from 34 to six major health topics during the prioritization process, each health topic still encompassed a substantial number of distinct outcomes. The large number of outcomes and outcome measures, along with the variation in results, makes it challenging to draw clear conclusions from the available evidence. For male and female fertility, there were respectively 28 and 20 outcomes or outcome measures that were considered valid enough as indicators for fertility but too different to be combined (Fig. 2). It was not always clear, in both primary studies and in the systematic review, whether these outcomes represented different concepts or if they were just different measurements of the same concept. For example, are sperm vitality and sperm morphology just different measurements of the same concept of male infertility or do they represent different outcomes from different biological processes involving RF EMF exposure. In the first case they can be pooled but in the latter case they should be considered separately.

For major health topics, it wasn't clear in some cases how and what should be measured as a valid and clinically important indicator of adverse health effects. In clinical medicine, very useful Core Outcome Sets (Kirkham and Williamson 2022) have been developed through expert and stakeholder consensus to identify the most important outcomes to always measure when evaluating the effects of interventions on a specific disease. Such an approach is not yet established in environmental health research but would be a valuable initiative.

5. Conclusions

This complex project has led to high-quality summaries of the evidence of effects of RF EMF on the most important health outcomes reported in the WHO prioritization survey in a standardized and transparent way. The results and conclusions from the present set of systematic reviews provide the most solid achievable basis for further evaluation of the effects of EMF exposure on health by the WHO task group, and the upcoming EHC Monograph of RF fields.

6. Disclaimer

The views expressed in this article are solely those of the authors and do not necessarily represent the views, decisions, or policies of the institutions with which they are affiliated.

CRediT authorship contribution statement

Jos Verbeek: Conceptualization, Visualization, Writing – original draft. **Hajo Zeeb:** Conceptualization, Writing – review & editing. **Emilie van Deventer:** Conceptualization, Writing – original draft, Writing – review & editing. **Sharea Ijaz:** Writing – original draft, Writing – review & editing. **Jean-François Doré:** Writing – review & editing. **Sarah Driessen:** Writing – review & editing. **Nicolas Roth:** Writing – review & editing. **Paul Whaley:** Writing – original draft, Writing – review & editing.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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