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The effect of exposure to radiofrequency electromagnetic fields on cognitive performance in human experimental studies: Systematic review and *meta*-analyses

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ABSTRACT

Background: The objective of this review is to evaluate the associations between short-term exposure to radiofrequency electromagnetic fields (RF-EMF) and cognitive performance in human experimental studies.

Methods: Online databases (PubMed, Embase, Scopus, Web of Science and EMF-Portal) were searched for studies that evaluated effects of exposure to RF-EMF on seven domains of cognitive performance in human experimental studies. The assessment of study quality was based on the Risk of Bias (RoB) tool developed by the Office of Health Assessment and Translation (OHAT). Random effects *meta*-analyses of Hedges's g were conducted separately for accuracy- and speed-related performance measures of various cognitive domains, for which data from at least two studies were available. Finally, the certainty of evidence for each identified outcome was assessed according to Grading of Recommendations Assessment, Development, and Evaluation (GRADE).

Results: 57,543 records were identified and 76 studies (80 reports) met the inclusion criteria. The included 76 studies with 3846 participants, consisting of humans of different age, sex and health status from 19 countries, were conducted between 1989 and 2021. Quantitative data from 50 studies (52 reports) with 2433 participants were included into the *meta*-analyses. These studies were performed in 15 countries between 2001 and 2021. The majority of the included studies used head exposure with GSM 900 uplink.

None of the *meta*-analyses observed a statistically significant effect of RF-EMF exposure compared to sham on cognitive performance as measured by the confidence interval surrounding the Hedges's g or the significance of the z-statistic.

For the domain *Orientation and Attention*, subclass *Attention – Attentional Capacity* RF-EMF exposure results in little to no difference in accuracy (Hedges's g 0.024, 95 % CI [−0.10; 0.15], $I^2 = 28$ %, 473 participants).

For the domain *Orientation and Attention*, subclass *Attention – Concentration / Focused Attention* RF-EMF exposure results in little to no difference in speed (Hedges's g 0.005, 95 % CI [−0.17; 0.18], $I^2 = 7$ %, 132 participants) and probably results in little to no difference in accuracy; it does not reduce accuracy (Hedges's g 0.097, 95 % CI [−0.05; 0.24], $I^2 = 0$ %, 217 participants).

For the domain *Orientation and Attention*, subclass *Attention – Vigilance* RF-EMF exposure probably results in little to no difference in speed and does not reduce speed (Hedges's g 0.118, 95 % CI [−0.04; 0.28], $I^2 = 41$ %, 247 participants) and results in little to no difference in accuracy (Hedges's g 0.042, 95 % CI, [−0.09; 0.18], $I^2 = 0$ %, 199 participants).

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For the domain *Orientation and Attention*, subclass *Attention – Selective Attention* RF-EMF exposure probably results in little to no difference in speed and does not reduce speed (Hedges's g 0.080, 95 % CI [−0.09; 0.25], $I^2 = 63$ %, 452 participants); it may result in little to no difference in accuracy, but it probably does not reduce accuracy (Hedges's g 0.178, 95 % CI [−0.02; 0.38], $I^2 = 68$ %, 480 participants).
For the domain *Orientation and Attention*, subclass *Attention – Divided Attention* RF-EMF exposure results in little to no difference in speed (Hedges's g −0.010, 95 % CI [−0.14; 0.12], $I^2 = 5$ %, 307 participants) and may result in little to no difference in accuracy (Hedges's g −0.089, 95 % CI [−0.35; 0.18], $I^2 = 53$ %, 167 participants).
For the domain *Orientation and Attention*, subclass *Processing Speed – Simple Reaction Time Task* RF-EMF exposure results in little to no difference in speed (Hedges's g 0.069, 95 % CI [−0.02; +0.16], $I^2 = 29$ %, 820 participants).
For the domain *Orientation and Attention*, subclass *Processing Speed – 2-Choice Reaction Time Task* RF-EMF exposure results in little to no difference in speed (Hedges's g −0.023, 95 % CI [−0.13; 0.08], $I^2 = 0$ %, 401 participants), and may result in little to no difference in accuracy (Hedges's g −0.063, 95 % CI [−0.38; 0.25], $I^2 = 63$ %, 117 participants).
For the domain *Orientation and Attention*, subclass *Processing Speed – >2-Choice Reaction Time Task* RF-EMF exposure results in little to no difference in speed (Hedges's g −0.054, 95 % CI [−0.14; 0.03], $I^2 = 0$ %, 544 participants) and probably results in little to no difference in accuracy (Hedges's g −0.129, 95 % CI [−0.30; 0.04], $I^2 = 0$ %, 131 participants).
For the domain *Orientation and Attention*, subclass *Processing Speed – Other Tasks* RF-EMF exposure probably results in little to no difference in speed and does not reduce speed (Hedges's g 0.067, 95 % CI [−0.12; 0.26], $I^2 = 38$ %, 249 participants); it results in little to no difference in accuracy (Hedges's g 0.036, 95 % CI [−0.08; 0.15], $I^2 = 0$ %, 354 participants).
For the domain *Orientation and Attention*, subclass *Working Memory – n-back Task* (0–3-back) we found Hedges's g ranging from −0.090, 95 % CI [−0.18; 0.01] to 0.060, 95 % CI [−0.06; 0.18], all $I^2 = 0$ %, 237 to 474 participants, and conclude that RF-EMF exposure results in little to no difference in both speed and accuracy.
For the domain *Orientation and Attention*, subclass *Working Memory – Mental Tracking* RF-EMF exposure results in little to no difference in accuracy (Hedges's g −0.047, 95 % [CI −0.15; 0.05], $I^2 = 0$ %, 438 participants).
For the domain *Perception*, subclass *Visual and Auditory Perception* RF-EMF exposure may result in little to no difference in speed (Hedges's g −0.015, 95 % CI [−0.23; 0.195], $I^2 = 0$ %, 84 participants) and probably results in little to no difference in accuracy (Hedges's g 0.035, 95 % CI [−0.13; 0.199], $I^2 = 0$ %, 137 participants).
For the domain *Memory*, subclass *Verbal and Visual Memory* RF-EMF exposure probably results in little to no difference in speed and does not reduce speed (Hedges's g 0.042, 95 % CI [−0.15; 0.23], $I^2 = 0$ %, 102 participants); it may result in little to no difference in accuracy (Hedges's g −0.087, 95 % CI [−0.38; 0.20], $I^2 = 85$ %, 625 participants).
For the domain *Verbal Functions and Language Skills*, subclass *Verbal Expression*, a *meta*-analysis was not possible because one of the two included studies did not provide numerical values. Results of both studies did not indicate statistically significant effects of RF-EMF exposure on both speed and accuracy.
For the domain *Construction and Motor Performance*, subclass *Motor Skills* RF-EMF exposure may reduce speed, but the evidence is very uncertain (Hedges's g −0.919, 95 % CI [−3.09; 1.26], $I^2 = 96$ %, 42 participants); it probably results in little to no difference in accuracy and does not reduce accuracy (Hedges's g 0.228, 95 % CI [−0.01; 0.46], $I^2 = 0$ %, 109 participants).
For the domain *Concept Formation and Reasoning*, subclass *Reasoning* RF-EMF exposure results in little to no difference in speed (Hedges's g 0.010, 95 % CI [−0.11; 0.13], $I^2 = 0$ %, 263 participants) and probably results in little to no difference in accuracy and does not reduce accuracy (Hedges's g 0.051, 95 % CI [−0.14; 0.25], $I^2 = 0$ %, 100 participants).
For the domain *Concept Formation and Reasoning*, subclass *Mathematical Procedures* RF-EMF exposure results in little to no difference in speed (Hedges's g 0.033, 95 % CI [−0.12; 0.18], $I^2 = 0$ %, 168 participants) and may result in little to no difference in accuracy but probably does not reduce accuracy (Hedges's g 0.232, 95 % CI [−0.12; +0.59], $I^2 = 86$ %, 253 participants).
For the domain *Executive Functions* there were no studies.
Discussion: Overall, the results from all domains and subclasses across their speed- and accuracy-related outcome measures according to GRADE provide high to low certainty of evidence that short-term RF-EMF exposure does not reduce cognitive performance in human experimental studies. For 16 out of 35 subdomains some uncertainty remains, because of limitations in the study quality, inconsistency in the results or imprecision of the combined effect size estimate. Future research should focus on construction and motor performance, elderly, and consideration of both sexes.
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The protocol for this review was registered in Prospero reg. no. CRD42021236168 and published in Environment International (Pophof et al. 2021).

1. Introduction

As the World Health Organization (WHO) (Verbeek et al. 2021) pointed out, exposure to radiofrequency electromagnetic fields (RF-EMF) has been steadily increasing, which might result in biological effects possibly related to health effects. In a survey among 300 RF-EMF experts and researchers WHO identified the health outcomes from a provided list of outcomes, which were prioritized by the 164 colleagues who responded to the survey. As a consequence, the WHO commissioned 10 systematic literature reviews for the most relevant outcomes, of which cognitive functioning is one. A systematic review evaluating the long-term effects of RF-EMF on cognition in human observational studies was recently published (Benke et al. 2024). The authors summarize that they "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" (Benke et al. 2024, page 12). However, there are several limitations, e.g. limited evidence due to few studies, the limited number of considered cognitive domains as well as the diversity of assessment tools of investigated cognitive domains: Therefore, further research based on a consensus about uniform methods of exposure and outcome assessment is recommended.

Investigation of potential effects of RF-EMF on cognitive performance is mainly motivated by the comparatively high RF-EMF exposure of the brain that can occur during mobile phone calls. Owing to the widespread use of RF-EMF transmitting devices among workers and in the general population, even small changes in performance measures such as accuracy, reaction time or performance speed may have a meaningful impact.

Biophysical mechanisms for potential RF-EMF-induced effects below the allowed exposure levels on cognition are unknown (WHO 2010). Concerning exposure levels resulting from mobile phones, thermal effects have been suggested (Danker-Hopfe et al. 2016; Loughran et al. 2013). The RF-EMF exposure might potentially improve, impair or have no effect on cognitive performance; and this effect may also depend on the investigated outcome, the applied cognitive challenge, the type and characteristics of exposure, as well as other factors. If there is indeed a causal RF-EMF exposure level dependent effect on cognitive function it is very likely, that it also depends on the spatial exposure level distribution in the brain.

Four *meta*-analyses (Barth et al. 2008; 2012; Valentini et al. 2010; Zubko et al. 2017) and several (systematic) reviews (Bodewein et al. 2022; Cook et al. 2002; 2006; Curcio 2018; D'Andrea et al. 2003a; 2003b; Hamblin and Wood 2002; Health Council of the Netherlands 2020; Hinrikus et al. 2021; 2022; Hossmann and Hermann 2003; Kwon and Hämäläinen 2011; Marino and Carrubba 2009; Martens 2005; Mortazavi et al. 2014; Regel and Achermann 2011; Rubin et al. 2011; Sienkiewicz et al. 2005; van Rongen et al. 2009; Wiedemann and Schütz 2011; Zhang et al. 2017) on possible effects of RF-EMF on cognition have been published to date. The reviews that included studies from the last 10 years considered either one cognitive domain only (Curcio 2018), did not consider performance outcomes (Zhang et al. 2017), looked at possible beneficial effects only (Mortazavi et al. 2014) or considered only studies on children (Bodewein et al. 2022; Sienkiewicz et al. 2005; Wiedemann and Schütz 2011).

Some of the earlier reviews reported facilitating effects of RF-EMF (Cook et al. 2002), especially if performing more complex tasks (Hamblin and Wood 2002). The magnitude of effects, observed in both directions, was considered to be only small, and not detrimental for health (Barth et al. 2008; Hossmann and Hermann 2003; van Rongen et al. 2009). Most of the more recent reviews concluded either that mobile phone-like EMF do not seem to induce effects (Barth et al. 2012; Valentini et al. 2010) or that there was no evidence of short-term effects (Zubko et al. 2017). The evidence for an effect was judged to be very weak (D'Andrea et al. 2003a) or substantially lacking with regard to impacts on attention (Curcio 2018).

The picture is similar in reviews on possible effects on children, but some authors stated that no clear conclusion could be drawn, since the number of studies is much smaller than on adults (Martens 2005; Sienkiewicz et al. 2005). It has also been concluded that there is no or only scant evidence for health hazard in children (Wiedemann and Schütz 2011). This is underlined by a systematic review on physiological and health-related effects of RF-EMF exposure in children (Bodewein et al. 2022) which included eleven experimental studies, of which six investigated effects of exposure on cognitive function. The authors concluded that the evidence from the experimental studies is inadequate to draw a conclusion regarding mobile phone-related RF-EMF exposure.

The inconsistencies in some of the studies and reviews led several authors of reviews to criticize the methods applied and recommend improved study designs, more sensitive measures and adequate statistics (Cook et al. 2006; Kwon and Hämäläinen 2011; Regel and Achermann 2011; Rubin et al. 2011).

An up-to-date systematic review is therefore needed to assess whether RF-EMF exposure may have an adverse effect on cognitive performance. In addition, a more comprehensive *meta*-analysis than previously published, including all cognitive functions studied to date, and including both speed- and accuracy-related outcome measures, will be conducted to provide a more complete picture of possible effects of RF-EMF. With respect to the rating of the study quality, only Zubko et al. (2017) and Bodewein et al. (2022) have carried out an assessment according to RoB. Only Bodewein et al. (2022) assessed evidence based on a GRADE approach. We applied both approaches in the present review and *meta*-analyses.

2. Methods

The detailed procedures of this systematic review have been outlined in a pre-defined protocol (Pophof et al. 2021), which has been registered in Prospero (CRD42021236168). This systematic review provides a comprehensive assessment of the following question concerning population, exposure, comparator, and outcome (PECO): What are the immediate effects of exposure to RF-EMF in the frequency range 100 kHz – 300 GHz (E) on cognitive performance (O) in humans (P) as compared to no or a lower exposure level (C)?

We define immediate effects as those that occur during or immediately after exposure within the given experimental time parameters and settings. Since possible mechanisms on the human brain and cognitive performance are not known, we did not set a minimum exposure duration.

2.1. Eligibility criteria

We included randomized experimental parallel-group and cross-over studies with at least two applied RF-EMF exposure levels (including sham or control) in a laboratory under controlled conditions, in which at least the participants were blind to the applied exposure level. We excluded studies with insufficient exposure contrast, lack of exposure characterization or co-exposure to EMF outside the specified frequency range. Studies that clearly stated that they were non-randomized and studies in which participants were not blinded to the exposure were excluded, because confounding and selection bias make it difficult to determine causal effects, and such studies do not add much to the evidence, especially when better quality studies are available. There was no restriction considering publication date or language, but only peer-reviewed articles that reported primary data were included. We excluded reviews, statements, reports, opinion papers, comments, editorials, conference abstracts, and proceedings. The eligibility criteria with regard to the PECO are summarized in Fig. 1.

2.2. Information sources

Electronic searches were conducted in five databases: PubMed (NLM), Embase, Scopus, Web of Science and EMF-Portal, a dedicated database of scientific literature on health effects of exposure to EMF. Searches were performed from May 2021 up until March 2nd 2023 for all databases (Supplementary Data 1, Table S1.1).

To identify eligible reports not identified through the electronic search, we checked the reference lists of relevant reviews identified through the electronic search.

2.3. Search strategy

The search strategy was developed for PubMed and was then adapted to the other databases. We used a detailed search strategy including keywords with synonyms, and in databases with a thesaurus (PubMed and Embase) we also used controlled vocabulary terms. The query combined terms related to the exposures and outcomes defined in the PECO statement above. We adjusted the search terms to achieve a balance of precision and recall in the results.

All individual search queries can be found in Pophof et al. (2021),

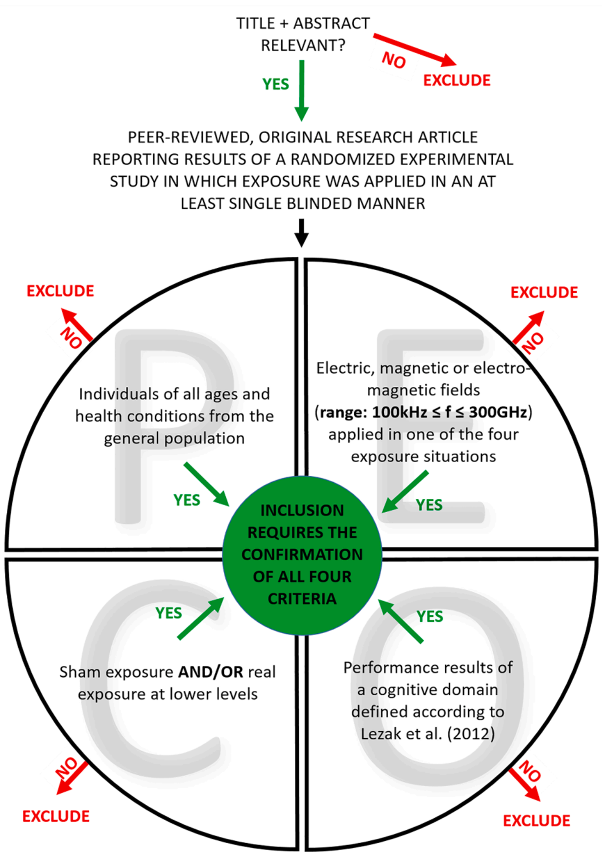

Fig. 1. Graphical summary of study selection process. The PECO questions could be answered in any order. Any single "no" response led to the exclusion of the study. For inclusion all questions had to be answered with "yes". For detailed description of the four predefined exposure conditions see Pophof et al. (2021).

Supplementary Data 1–5. Search limits used in particular databases are listed in Supplementary Data 1, Table S1.2.

2.4. Selection process

Records were managed using Covidence, a web application for conducting systematic reviews (https://www.covidence.org/). In a first step, two different reviewers out of the pool of authors independently checked the relevance of the identified papers based on titles and abstracts. All authors were involved in study selection. At this stage, we excluded records that were clearly not relevant (Fig. 1). This resulted in a list of references for which, in a second step, two reviewers independently assessed the inclusion and exclusion criteria based on the full-text of the article. Excluded studies and the reasons for exclusion were documented (Supplementary Data 2). If abstracts or articles required translation into another language to determine their eligibility, we used Google Translate. In all steps, any disagreement between the two reviewers was resolved by discussion. If no consensus could be reached, a third reviewer was consulted. If findings from a study were described in more than one report, we considered all reports together as one study. If one publication reported several independent experiments, they were considered as separate studies.

2.5. Data collection process

For each study included in the review, a standard set of details was extracted from the relevant publication(s) (Pophof et al. 2021, Supplementary Data 6). In short, we collected data on:

- the report (e.g., author, year, source of publication)
- the study (e.g., country, sponsorship, conflict of interest, study design)
- the population (e.g., number, age, sex)
- exposure parameters (e.g., level/intensity, frequency, modulation)
- outcomes and measurements (e.g., domains, tasks, numerical values), and
- methodical issues important for RoB evaluation (e.g., randomization, counterbalancing, blinding).

We used a standardized data extraction form in Microsoft Excel instead of Covidence, as originally planned, because the large amount of data could be handled more efficiently in Excel. One reviewer extracted the relevant data from each included study. In order to ensure completeness and accuracy, a second reviewer checked the extracted study information against the respective report(s) as a quality control measure. All authors were involved in data extraction. When studies conducted by the authors of this review were included, we made sure that these authors did not extract data from their own studies.

2.6. Dealing with missing data

For all studies for which missing data precluded the determination of eligibility, assessment of risk of bias, or inclusion in the data synthesis, information was requested by email from the corresponding author. If no response was received, we followed up twice (see Supplementary Data 3). If there was still no response, we considered the data as missing.

2.7. Outcomes

We assessed the following cognitive domains according to Lezak et al. (2012):

(1) Orientation and attention
(2) Perception
(3) Memory
(4) Verbal functions and language skills
(5) Construction and motor performance
(6) Concept formation and reasoning, and
(7) Executive functions.

The domain-specific performance can either be measured in terms of accuracy-related outcome measures (e.g., correct, false, missed responses) and/or in terms of speed-related outcome measures (e.g., reaction time, response speed, processing time). Beyond those tests described by Lezak et al. (2012), Fulda and Schulz (2001) provide a list of further tests and group these according to Lezak's taxonomy (2012). If a particular test was not indexed in either source, it was grouped according to the primary measure of cognitive performance required as determined by one of the data extractors (CS). As outcomes for this systematic review, we define the subclasses of the domains as described by Lezak et al. (2012, Part II The Compendium of Tests and Assessment Techniques, p. 391 ff.) (Table 1). (See also *Deviations from the protocol*).

2.8. Risk of bias assessment

We applied the RoB Rating Tool for Human and Animal Studies developed by the National Toxicology Program Office of Health Assessment and Translation (OHAT) (NTP, 2019; Rooney et al. 2014; 2016) in order to assess the RoB of included studies. This tool, which is based on questions that have to be answered by the assessors, has various forms for different study designs; we primarily used the questions designed for human clinical trials. The OHAT questions for human clinical trials, however, are designed primarily for parallel-group studies. To make sure that cross-over studies were adequately assessed, we added three further questions. One of these questions was

Table 1
Cognitive domains and subclasses: Seven cognitive domains and 23 subclasses according to Lezak et al. (2012) included in this systematic review are displayed.

Domain	Subclasses			Domain and subclasses not represented in reviewed studies
D1 Orientation and Attention (183/127)	**Attention (59/39):** • Attentional Capacity (6/5) • Concentration / Focused Attention (8/6) • Vigilance (12/7) • Selective Attention (25/15) • Divided Attention (8/6)	**Processing Speed (56/38):** • Simple Reaction Time (21/14) • 2-Choice Reaction Time (14/9) • >2-Choice Reaction Time (10/7) • Other tasks (11/8)	**Working Memory / Mental Tracking (68/50):** • 0-back task (9/8) • 1-back task (16/12) • 2-back task (17/13) • 3-back task (14/10) • Mental Tracking (12/7)	**Orientation (0/0)**
D2 Perception (9/5)	**Visual Perception (6/5)**	**Auditory Perception (3/0)**		**Tactile Perception (0/0)** **Olfaction (0/0)**
D3 Memory (27/12)	**Verbal Memory (13/8)** **Visual Memory (13/4)**			**Tactile Memory (0/0)** **Incidental Learning (0/0)** **Prospective Memory (0/0)** **Remote Memory (0/0)** **Forgetting (0/0)** [Unspecified (1/0)]*
D4 Verbal Functions and Language Skills (2/0)	**Verbal Expression (2/0)**			**Aphasia (0/0)** **Verbal Comprehension (0/0)** **Verbal Academic Skills (0/0)**
D5 Construction and Motor Performance (4/4)	**Motor Skills (4/4)**			**Drawing (0/0)** **Assembling and Building (0/0)**
D6 Concept Formation and Reasoning (14/9)	**Concept Formation (3/0)**	**Reasoning (4/3)**	**Mathematical Procedures (7/6)**	
D7 Executive Functions (0/0)				**Volition (0/0)** **Planning and Decision Making (0/0)** **Purposive Action (0/0)** **Self-Regulation (0/0)** **Effective Performance (0/0)**

The first number in brackets refers to the total number of studies that were conducted in a certain domain or subclass, the second number represents the number of studies that provided adequate numerical data to be considered in the *meta*-analyses.The subclasses verbal and visual memory were combined within one *meta*-analysis.

* unspecified verbal learning and memory test in Eibert et al. 1997.

adapted from the OHAT questions for experimental animal studies, and the other two were adapted from the Cochrane RoB 2.0 tool (Higgins et al. 2016; see Pophof et al. 2021, Supplementary Data 8). These three additional questions are indicated in Supplementary Data 4.

Each item, in the form of a specific question, was rated with one of four options:

(i) definitely low risk of bias,
(ii) probably low risk of bias,
(iii) probably high risk of bias or no information (not reported) / unclear risk of bias, or
(iv) definitely high risk of bias.

Considerations and guidance for rating the single items are given in Supplementary Data 8 of the protocol (Pophof et al. 2021). In Supplementary Data 4 we add details on how this guidance was applied.

The RoB was assessed independently by two different reviewers out of the pool of authors. All authors were involved in the RoB assessment. We used a standardized form in Microsoft Excel instead of Covidence, as originally planned, because the large amount of data could be handled more efficiently in Excel. Any disagreement was resolved by discussion. When studies conducted by the authors of this review were included, we made sure that these authors did not assess the RoB of their own studies.

After assessing RoB for each single question, we assessed RoB for each study according to OHAT (NTP, 2019) tiers as follows. First, we identified two key questions which we considered more important than others to evaluate the overall RoB in this context: question 5 (blinding) and question 9 (outcome assessment). Since studies using a non-randomized design were not included in the review, randomization was not considered a key question. Similarly, for a mechanistic understanding as well as for dose–response analyses a reliable, spatially-resolved exposure characterization is very important. However, all included studies were performed with a sufficient exposure contrast, so that even for the studies with "definitely high risk of bias" regarding question 8 (exposure characterization) we can be confident that the subjects were actually exposed, although the absolute level as well as the spatial distribution of the exposure in the head are not well known. Based on these considerations the tiers were assigned as follows:

1st tier (low overall risk of bias): Studies with all questions assessed as "definitely or probably low risk of bias" were assigned low overall risk of bias. Additionally, we allowed "probably high risk of bias" in one single question if it was not one of the two key questions 5 and 9 on blinding and outcome assessment, respectively.

3rd tier (high overall risk of bias): All studies assigned "definitely high risk of bias" in any two or more questions, or in at least one of the two key questions were rated as having a high overall risk of bias. This means that, for example, all studies in which only the volunteers were blinded (single-blind) fall into this category. Furthermore, studies having a definitely high risk of bias in any other question, but additionally a probably high risk of bias in one of the key questions, were also assigned an overall high risk of bias.

2nd tier (medium overall risk of bias): All remaining studies.

2.9. Meta-analyses

2.9.1. Effect measures

From included studies we compiled all data which enable the calculation of Hedges's g, i.e., means and standard deviations / standard errors, and considered how to best utilize these measures across studies. For more detailed information on how effect sizes were calculated, especially for cross-over studies, see Supplementary Data 5.

2.9.2. Synthesis methods

For the synthesis we defined a specific outcome as described above and summarized all studies investigating this outcome. Additionally, we considered accuracy- and speed-related outcome measures separately for each outcome. When a study reported multiple outcome measures per domain and/or subclass, in order to best inform the overall synthesis and to avoid *meta*-analysing highly correlated outcomes (Higgins et al. 2023), we considered in the *meta*-analyses those outcome measures that were reported in most other studies. All remaining outcome measures which could not be included in the *meta*-analyses were synthesized narratively. For example, Besset et al. (2005) applied three different memory tests (Rey's Auditory Verbal Learning Test, AVLT; Benton Visual Retention Test; Perceptual Priming Task/Implicit Memory) within one study (D3 *Memory*, Supplementary Data 6, p. 26) and reported four accuracy measures in total. We selected one of two reported accuracy measures from the AVLT for the *meta*-analysis ("MA" in the last column of table Supplementary Data 6), since this test was also used by other authors (Keetley et al. 2006). The remaining three accuracy outcome measures published by Besset et al. (2005) were considered narratively ("N" in the last column of table Supplementary Data 6), i.e., effect sizes were calculated, data were visualized and results were also reported. The process is graphically illustrated in Fig. 2. Supplementary Data 6 provides an overview of all outcomes of all studies, categorized by domains, subclasses, type of outcome (accuracy, speed, other) as well as the type of analysis of data ("MA": suitable data to be considered in the *meta*-analysis; "N": processed narratively). If studies did not report results that offered numerical information to be used in a *meta*-analysis (studies marked red in Supplementary Data 6), we presented results descriptively (Table 4).

For all speed- and accuracy-related outcome measures the effect of RF-EMF exposure was compared to sham exposure. If several levels of RF-EMF exposures were considered in a study, these were pooled according to the following formulae (see also Zubko et al. 2017):

$$Combinedmean = ((n_1 * \overline{X}_1) + (n_2 * \overline{X}_2))/combined\ n \quad (1)$$

$$CombinedSD = \sqrt{(a+b)/(combined\ n - 1)} \quad (2)$$

with $a = ((n_1 - 1) * (SD_1 * SD_1)) + ((n_2 - 1) * (SD_2 * SD_2))$
$b = ((n_1 * n_2) / \text{combined } n) * ((\overline{X_1} * \overline{X_1}) + (\overline{X_2} * \overline{X_2}) - 2 * (\overline{X_1} * \overline{X_2}))$.
combined $n = (n_1 + n_2)$.
where n = number of participants.
$\overline{X}$ = mean value.
1: condition (1).
2: condition (2).

For each outcome measure, where at least two studies reported numerical values that could be appropriately combined, we synthesized the Hedges's g estimates using random effects *meta*-analysis. Hedges's g < 0 indicates a negative effect, for example, a longer reaction time or a lower accuracy, Hedges's g > 0 indicates a positive effect, for example, a faster reaction time or a higher accuracy. Absolute values of Hedges's g of 0.2 represent a small effect, 0.5 a moderate effect and 0.8 a large effect (Cochrane Handbook 6.4, Higgins et al. 2023). The z-statistic was used to test whether the overall pooled effect was statistically significantly different from 0. For outcomes not selected for the *meta*-analyses, effect sizes were computed, visualized and analysed descriptively, specifically in order to assess the consistency of the results.

The I^2-statistic was used to assess heterogeneity. By conducting subgroup analyses, we investigated possible reasons for heterogeneity between studies for those *meta*-analyses in which the I^2-statistics > 30 %, which according to Cochrane Handbook (Higgins et al. 2023) is a value that may represent at least a moderate heterogeneity. An I^2 up to 40 % might not be important, values from 30 % to 60 % may represent a moderate heterogeneity, 50 % to 90 % may represent a substantial heterogeneity, and I^2 values > 75 % reflect a considerable heterogeneity.

Investigated subgroups were:

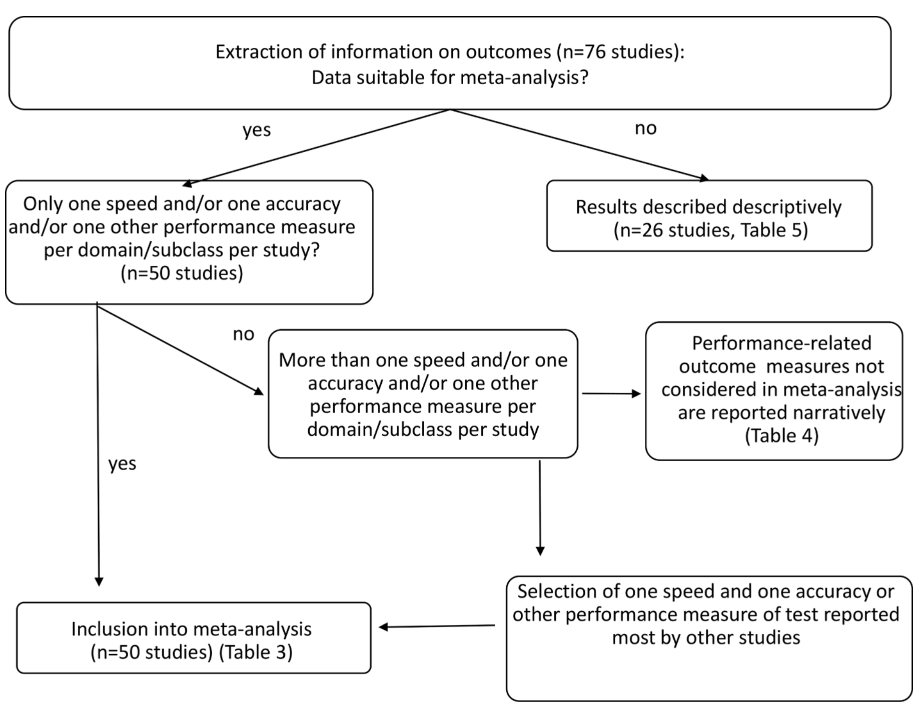

Fig. 2. Decision tree for data extraction for outcomes.

- Study quality: tier 1 and 2 vs tier 3 (RoB)
- Study design: cross-over vs parallel-group
- Sample size: < 30 vs ≥ 30
- Population: adults without idiopathic environmental intolerance attributed to EMF (IEI) which for some outcome measures includes the study in narcoleptic patients vs a pooled group of adults with and without IEI; adults vs children and/or adolescents
- Sex: male vs female vs male and female
- Exposed part of the body: head vs whole body
- Funding source: government or mixed vs industry or not reported
- Blinding: double-blind vs single blind or blinding not reported (Supplementary Data 12).

Statistical analyses were carried out using the software package Comprehensive Meta-Analysis V3.

2.9.3. Sensitivity analysis

2.9.3.1. Publication bias assessment. We assessed publication bias for all *meta*-analyses based on guidance found in the Cochrane Handbook (Higgins et al. 2023). For all *meta*-analyses, we created and visually inspected funnel plots. Additionally, as recommended by Egger et al. (1997) and Sterne et al. (2011), where 10 or more studies were assessed in a given *meta*-analysis, we conducted the Egger's test using a threshold for significance of $p < 0.1$.

2.9.3.2. Certainty assessment. We assessed the certainty of evidence of each body of evidence according to the "Grading of Recommendations Assessment, Development, and Evaluation" (GRADE) approach (Guyatt et al. 2011) and in line with the study protocol (Pophof et al. 2021).

In the GRADE approach, a body of evidence comprising randomized controlled experimental studies starts as high-certainty evidence. We subsequently considered downgrading the certainty of evidence as follows:

- Study limitations: Downgrading by one level if at least 50 % but less than 75 % of the studies for a result were tier 3 regarding RoB, downgrading by two levels if at least 75 % of the studies were tier 3.
- Indirectness of evidence: We did not downgrade for indirectness, because we included only studies directly related to the PECO question (see Pophof et al. 2021).
- Inconsistency of results: We graded down by one level if the heterogeneity was moderate or substantial (30 % $< I^2 <$ 90 %). We graded down by two levels if the heterogeneity was $I^2 \geq$ 90 %. Where $I^2 >$ 30 %, yet subgroup analyses indicate an $I^2 <$ 30 % in subgroups including solely 1st and 2nd tier studies or including only studies with 30 or more participants, we did not downgrade, as we considered the heterogeneity to be explained (Guyatt et al. 2011).
- Imprecision: If the value of Hedges's g was between −0.2 and 0.2 and the 95 % CI included either −0.2 or + 0.2, we graded down the certainty of evidence for the lack of an effect by one level. If the value of Hedges's g was outside the interval [−0.2; 0.2] and the 95 % CI included 0, we graded down the certainty of evidence for the presence of an effect by one level. We graded down by one additional level if the 95 % CI was wider than [−1.0; 1.0].
- We downgraded certainty of evidence where both the Egger's test (i.e., $p < 0.1$) and the visual assessment of the funnel plot (i.e., asymmetry) indicated the possibility of publication bias.

This operationalization of inconsistency and imprecision is more stringent than defined in the protocol (Pophof et al. 2021).

To communicate the results of certainty assessment we used the guideline by Santesso et al. (2020).

3. Results

3.1. Search results

Over all searches in all databases a total of 57,543 references were retrieved. The search dates and the number of records found in each database are summarized in Supplementary Data 1, Table S1.1. The records were imported into the reference management software EndNote® for deduplication. After deduplication, 23,450 records remained and were imported into Covidence.

3.2. Study selection

The remaining 23,450 studies were screened at the level of title and abstract. 23,205 studies were clearly irrelevant and therefore excluded. Two studies could not be retrieved because the text was not available. Two more potentially relevant studies were identified from citation searching in reviews. Altogether 245 studies were assessed for eligibility based on full-text (Fig. 3, PRISMA flow diagram).

3.3. Excluded studies

We excluded 165 studies at the full-text screening stage. Ninety-nine of these were reviews, which were excluded after screening the references for further eligible studies. We excluded studies for various reasons, including: no cognitive tasks performed, study design was observational and/or non-randomized, study conducted in animals, no investigation of RF-EMF, no proper description of the exposure, insufficient exposure contrast, no peer review, study type was report or proceedings. Authors of 14 studies (14 reports) were contacted and asked to provide missing information to decide about inclusion or exclusion (Supplementary Data 3). A full list of studies not retrieved or excluded, with reason for exclusion, is given in Supplementary Data 2.

3.4. Study characteristics

Study characteristics of all included studies are presented in Supplementary Data 7. We included 76 studies published in 80 reports in the systematic review and 50 studies (52 reports) in the *meta*-analyses. The included studies originate from 18 different countries, most of them from Germany (12) and Finland (11). The studies were published over a timespan of more than 30 years (1989 – 2021). Altogether, 3846 humans were tested in the included studies for the systematic review.

Twenty-three studies were funded by governmental institutions, five by industry, 38 had a mixed funding and ten did not report the source of funding. Sixteen studies reported having no conflict of interest, one study reported one of the authors to have a conflict of interest, and 59 studies did not report if there was a conflict of interest or not.

Fifty-eight studies used a cross-over design, six studies a parallel-group design, and 12 studies used a cross-over design for parallel-groups.

Seventy-one studies investigated healthy adults, three studies adolescents (Leung et al. 2011; Loughran et al. 2013; Riddervold et al. 2008), five studies children (Haarala et al. 2005; Loughran et al. 2013; Maier et al. 2004b; Movvahedi et al. 2014; Preece et al. 2005), and one study the elderly (Leung et al. 2011). Persons with IEI were tested in seven studies (Eltiti et al. 2009; Furubayashi et al. 2009; Malek et al. 2015; Regel et al. 2006; Wallace et al. 2012; Wiholm et al. 2009; Wilén et al. 2006), patients with narcolepsy in one study (Jech et al. 2001). Eleven studies investigated more than one subgroup. The number of individuals tested in a single study ranged from eight to 200. Forty-eight studies investigated men and women, 24 solely men, one solely women, and three did not report sex.

Sixty-six studies tested head exposure, ten studies whole body exposure. Studies using whole body exposure reported whole body SAR values up to 0.01 W/kg. Studies with localized exposure of the head

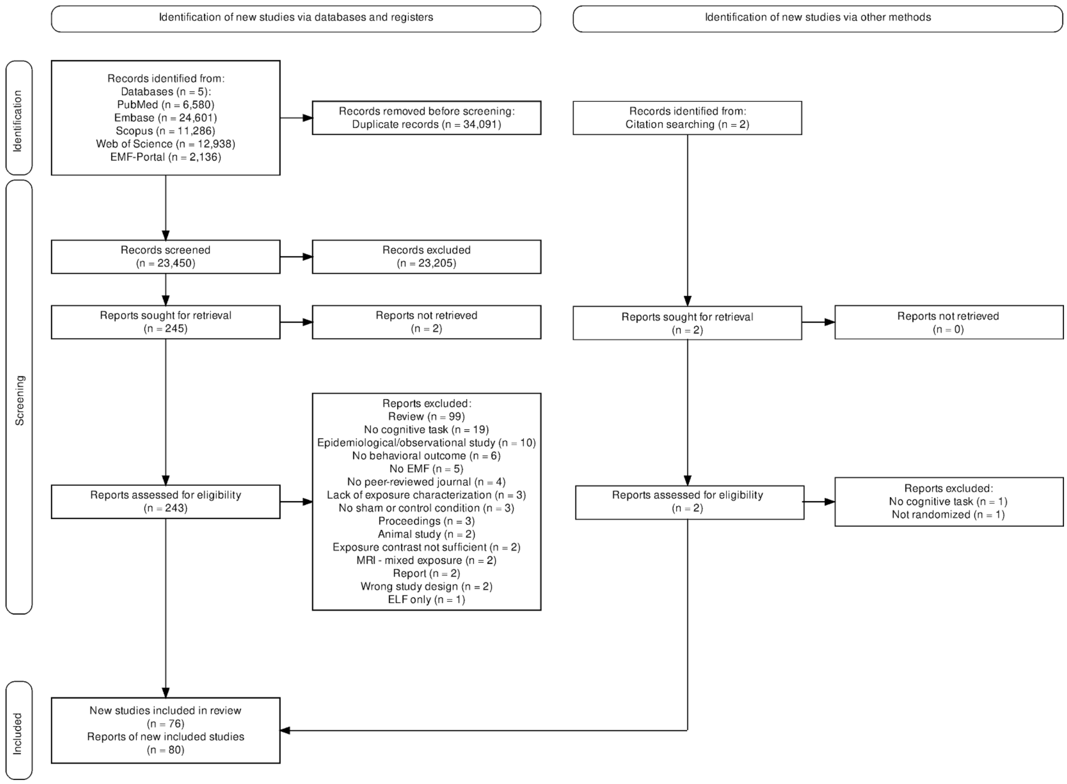

Fig. 3. Prisma flow diagram. Abbreviations: ELF – Extremely Low Frequency, EMF – electromagnetic field, MRI – Magnetic Resonance Imaging, n – number.

applied maximum 10 g averaged SAR values in the range 0.006 – 6 W/kg. Thirty-two studies used especially developed exposure systems, 38 studies used modified mobile phones, and one study a modified TETRA handset for exposure. Three studies used mobile phones and two studies WiFi devices. The investigated frequency ranged from 400 MHz to 2450 MHz; most studies (n = 54 studies) were performed at 900 MHz. Besides continuous wave and pulse-modulated exposures, various signal modulations that resemble mobile communication standards (e.g., GSM, UMTS, LTE, TETRA, WiFi) were used. GSM (uplink)-like modulations predominated and were investigated in 48 studies.

All studies used either no exposure or sham exposure for control. The exposure device was either switched off, or it remained on but did not emit any RF-EMF field, or the remaining emission was negligible.

Individual studies investigated one to a maximum of five outcome domains (see methods, Lezak et al. 2012). Domains 1–6 were addressed by the studies, whereas none of the tests was categorized as domain 7 (*Executive Function*) according to the classification of Lezak et al. (2012) (Table 1). Domain 1 (*Orientation and Attention*) was investigated in 64 studies, domain 2 (*Perception*) in nine studies, domain 3 (*Memory*) in 20 studies, domain 4 (*Verbal Functions and Language Skills*) in two studies, domain 5 (*Construction and Motor Performance*) in four studies and domain 6 (*Concept Formation and Reasoning*) in ten studies.

Of the included 76 studies, 50 studies (52 reports) with 2433 subjects were included in the *meta*-analyses. The remaining 26 studies (28 reports) could not be included in *meta*-analyses due to missing appropriate numerical values.

A statistical comparison of characteristics of the studies included in the systematic review and the *meta*-analyses is presented in Supplementary Data 8. The studies included and not included in *meta*-analyses did not differ significantly with respect to most characteristics listed in Supplementary Data 8, indicating that most probably there will be no bias in reported results based on *meta*-analyses. Statistically significant differences between the study samples were only observed for the following two study characteristics' distributions (Supplementary Data 8):

a) Funding source: This difference is reflected in particular in the number of studies which did not report the funding source. Only very few studies which contributed to the *meta*-analyses did not report funding source, in contrast to roughly one third in the other study sample. On the other hand, some of the studies that contributed to the *meta*-analyses reported an industry funding, while none of the non-contributing studies reported to be funded by industry.
b) *SAR:* In roughly half of the studies SAR values between 0.5 and 5 W/kg were applied, with a slightly higher proportion in the sample of studies that were not included in the *meta*-analyses, whereas almost approximately one quarter of studies did not report SAR values at all, with a lower proportion in the *meta*-analyses study sample.

3.5. *Reported study results*

Altogether, 42 studies did not report a significant effect of RF-EMF exposure on any investigated domain / subclass of cognitive function. Eighteen studies reported favourable effects in at least one of the performed tests, for example, slightly shorter reaction times or more accurate responses. Ten studies reported unfavourable effects, for example, prolonged reaction times or increased number of incorrect responses. Five studies reported favourable as well as unfavourable effects, as they investigated more than one outcome measure and the direction of the effect varied. One study did not report statistical methods, and the description of the outcome was insufficient for further interpretation.

3.6. *Data extraction and aggregation for the meta-analyses*

Out of the 76 studies we contacted the authors of 40 studies for additional information in order to calculate an effect size. The efforts made to obtain this information are summarized in Supplementary Data 9.

Twenty-one studies (representing 22 reports) reported standard errors of means (SEM), which were converted to standard deviations (SD).

Several studies reported results separately for:

a) left and right hemisphere exposure,
b) participants from different countries,
c) performance for targets and non-targets,
d) morning and afternoon assessments,
e) men and women,
f) first and second session of a test for the same exposure, and
g) high and low probability of frequency of appearance of stimuli.

For those studies (Supplementary Data 9, Table S9.1) data were aggregated to combined means, and SDs were calculated separately for the sham and exposure conditions applying formulae (1) and (2) for the respective conditions. Furthermore, several studies reported results for more than one verum exposure besides sham exposure. In the following cases results were also pooled for the exposure condition:

- CW and pulsed exposure,
- low and high TETRA exposure level,
- low and high UMTS exposure level,
- low and high GSM exposure level,
- GSM and UMTS exposure,
- low and high GSM and UMTS exposure level,
- GSM 900, GSM 1800 and UMTS, and
- two modulation frequencies.

Additionally, results reported separately for subjects with and without self-reported sensitivity to electromagnetic fields (IEI) were pooled. In the protocol, we stated that these would be analysed separately, but with hindsight we find that there are only seven studies, in which subjects with and without IEI were investigated. Only six of the seven studies provide numerical data to be used to calculate effect sizes. The data from these six studies do not allow a detailed analysis following the approach taken in this paper.

Altogether, 26 studies did not report numerical values, which allow the calculation of effect sizes, and could thus not be included in the *meta*-analyses. Finally, quantitative data which allow the calculation of effect sizes were available for 50 studies.

3.7. Cognitive domains

Supplementary Data 7 indicates that none of the studies investigated RF-EMF effects on D7 *Executive Functions*. For the other six domains one or more subclasses are covered by the tests applied in the studies (Table 1).

For two of the domains, D1 *Orientation and Attention* and D6 *Concept Formation and Reasoning*, *meta*-analyses were run on different subclasses (Table 1). If speed-related data were available for at least two studies and if accuracy-related data were available for at least two studies, two *meta*-analyses were performed per domain or for a subclass, respectively, one for speed-related outcome measures and one for accuracy-related outcome measures. Data of subclasses were aggregated if the number of available outcome measures for a *meta*-analysis was low (see visual and verbal memory in Table 1).

For a detailed list of tests per study, domain, and subclass, respectively, see Supplementary Data 6. These data also include information on outcome measures which have been included in the *meta*-analyses.

3.8. Risk of bias in studies

A detailed overview of the RoB evaluation across all included studies and outcome domains is given in Fig. 4. Supplementary Data 10 provides the full RoB report. Overall, the quality of evidence is mixed, with half of the studies (50 %) classified as 2nd tier, 28 % as 3rd tier, and only 22 % as 1st tier. The quality of studies that contain data for *meta*-analyses (1st tier: 30 %, 2nd tier: 44 %, 3rd tier: 26 %) was slightly higher than the quality of the studies that did not contain data for *meta*-analyses (1st tier: 8 %, 2nd tier: 62 %, 3rd tier: 31 %) (Supplementary Data 10, Fig. 4). Key findings from the RoB assessment are summarized below.

Selection bias: A considerable proportion of studies appears to be subject to selection bias, as only slightly more than half of the studies provide direct or indirect evidence for proper randomization and balanced allocation of participants to study groups[3] (only relevant for cross-over studies). In the majority (75 %) of studies it was not reported whether the allocation of participants to study groups was concealed both from the research personnel and the subjects.

Performance bias: All except two studies provide direct or indirect evidence that exposure-related as well as exposure-unrelated experimental conditions were likely identical for the exposure and sham sessions, although there were some deficits in the control or reporting of non-exposure-related conditions (such as daytime of experiment) for some of these studies (rated probably low risk of bias). One very critical issue is the blinding status of participants and experimenters, as their expectations can consciously or unconsciously affect the outcome of an experiment. Direct or indirect evidence for proper double-blinding was reported in 64 % of studies, for example, computer-controlled exposure systems, measures for preventing acoustic or thermal perception. On the other hand, 24 % of studies were single-blind, and in the rest of the studies it was stated that they were blinded, but they did not provide sufficient information on blinding measures. In the majority (73 %) of the cross-over studies, the exposure and sham sessions were conducted on different days or sufficient time was left between the sessions ($\geq$24 h), making the occurrence of carry-over effects unlikely. For the rest of the studies carry-over effects cannot be ruled out, because the experiment was either performed on the same day within a single session, or insufficient information on this issue was reported.

Attrition / exclusion bias: Only very few studies are subject to attrition / exclusion bias. There was no direct evidence for this type of bias and only two studies did not report sufficient information on drop-out numbers and handling. In the majority of studies, the drop-out rate was less than 20 %, and those who reported higher values also reported reasons and/or considered this issue in the data analysis.

Detection bias: Exposure generation and assessment was rated the highest RoB of all RoB questions. Although the assessment of the magnitude of the maximum spatial SAR was adequate in the majority of studies, less than one third (29 %) of all included studies provided exposure data that would allow dose–response analyses based on adequately assessed and reported spatially resolved exposure levels in the brain (or on a reported study design and exposure details that would allow a post-hoc determination of spatially resolved exposure levels).

In contrast, in the majority of studies (72 %) well established cognitive tests were applied and outcome assessors were blinded. However, 28 % of studies were probably or definitely at high risk of bias, because the outcome assessors were not blinded or the blinding status of the outcome assessors was unclear. Because it turned out that blinding rather than inadequate tests was the main determinant for high risk of bias in the outcome assessment, there is a high level of redundancy in the probably and definitely high risk of bias ratings in the key questions 5 (blinding) and 9 (outcome assessment) as well as in the corresponding tier rating.

Selective reporting bias: 42 % of studies reported numerical values and dispersion measures for all measured outcomes, and an additional 51 % of studies either reported numerical values for some of their outcomes or only showed figures or reported outcome with insufficient detail, such as only reporting statistical significance levels. Only three studies (4 %) appeared to report outcomes selectively, and two studies (3 %) did not report outcomes but only provided overall verbal descriptions of their results on cognitive outcome measures.

[3] "Group" means subjects / persons / volunteers allocated to a fixed exposure condition or exposure condition sequence.

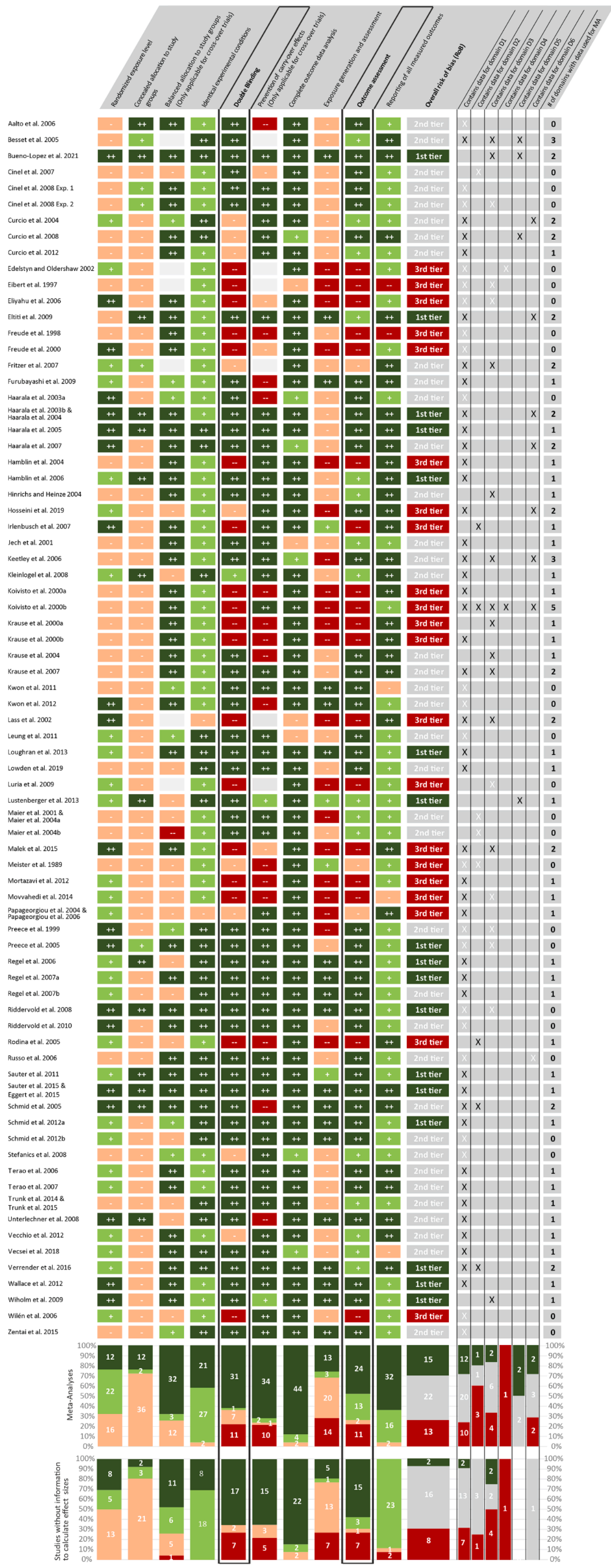

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Fig. 4. Summary of RoB ratings and available data. Risk of Bias (left): For each study the assignments of the RoB ratings (++ definitely low RoB, + probably low RoB, – probably high RoB, – – definitely high RoB) for each RoB question as well as the assignment to overall RoB tier are presented. The black frames indicate key RoB questions that are used to assign the overall RoB tiers. Available Data (right): All studies included in the systematic review were screened for eligible data. Studies that contain adequate data for calculating effect size estimates for *meta*-analyses are marked with a black X in the column of the respective domain to which the data contributes. In contrast, a white X denotes studies which contain data that cannot be used for computing effect sizes. In the bottom part of the figure, the distribution of the overall RoB tiers attributed to domains or studies as well as the distribution of the detailed RoB ratings of the studies broken down by RoB question is summarized for the categories "Meta-analyses" and "Studies without information to calculate effect sizes". Abbreviations: D1 – D6 – Domain 1 – Domain 6, MA – *meta*-analysis, RoB – Risk of Bias.

The distribution of RoB in the cognitive domains for which at least nine studies provided data (D1, D2, D3, D6) is roughly similar to the overall distribution of RoB. Only two studies contributed to D4 *Verbal Functions and Language Skills*, both 3rd tier. Of the four studies that investigated D5 *Construction and Motor Performance*, two were 1st tier and two 2nd tier.

3.9. Effects of RF-EMF exposure on cognitive domains

For the sake of clarity, within domains the results are summarized by subclasses. Within subclasses results are always presented in the following order:

1) Results of the *meta*-analysis for speed-related outcome measures,
2) Results of the *meta*-analysis for accuracy-related outcome measures,
3) Results for quantitative data, which were not considered in the *meta*-analyses (narrative synthesis), and
4) Review of studies, which could not be considered in the *meta*-analyses and narrative assessments.

The latter results refer to the 26 studies without suitable numerical data, while the first three analyses are based on 50 studies (52 reports) of which 36 provide data for *meta*-analyses for accuracy-related outcome measures and 40 studies provide corresponding data for speed-related outcome measures. Out of the 26 studies, which are discussed in the fourth chapter for each subclass, three report accuracy-related outcome measures only, two speed-related outcome measures only, 17 report both, three report an order threshold for the detection of a stimulus, and one does not report the cognitive outcome at all. All 76 studies compared results under RF exposure to performance in a sham control condition. The median sample size of the 50 studies is n = 24 participants (interquartile range: [40; 60]), for the 26 studies median sample size is n = 36 participants (interquartile range: [16; 96]).

3.9.1. Domain 1 Orientation and Attention

3.9.1.1. Attention - Attentional Capacity. The subclass *Attentional Capacity* of the cognitive domain *Orientation and Attention* was investigated in six studies. Five studies provided information to be used in the *meta*-analysis of accuracy-related outcome measures (Besset et al. 2005; Eltiti et al. 2009; Fritzer et al. 2007; Keetley et al. 2006; Malek et al. 2015) (Supplementary Data 6).

3.9.1.1.1. Meta-analysis of speed-related outcome measures. No study reported speed-related outcome measures.

3.9.1.1.2. Meta-analysis of accuracy-related outcome measures. The result of the *meta*-analysis does not indicate a statistically significant effect of RF-EMF exposure on *Attentional Capacity* (Hedges's g 0.024, 95 % CI [−0.101; 0.149], I^2 = 27.9 %; Table 2). Since heterogeneity as assessed by I^2 was low, there was no need for subgroup analyses.

Table 2
Meta-analyses – summary. Heterogeneity measures, Hedges's g and 95% confidence interval (CI) for speed- and accuracy-related outcome measures for domains and subclasses of cognitive performance under RF exposure as compared to sham exposure.

Domain	Subclass	outcome measure	n - studies	n - subjects	Hedges's g	95% CI	z	p	p	I^2	Tau
D1	Attention - Attentional Capacity	Speed									
		Accuracy	5	473	0.024	[−0.101; 0.149]	0.377	0.706	0.236	27,887	0.074
	Attention - Concentration/Focused Attention	Speed	3	132	0.005	[−0.171; 0.180]	0.052	0.958	0.343	6561	0.041
		Accuracy	4	217	0.097	[−0.049; 0.244]*	1.303	0.193	0.504	0.000	0.000
	Attention - Vigilance	Speed	7	247	0.118	[−0.044; 0.279]*	1.430	0.153	0.117	41,050	0.140
		Accuracy	6	199	0.042	[−0.094; 0.178]	0.609	0.542	0.846	0.000	0.000
	Attention - Selective Attention	Speed	13	452	0.080	[−0.089; 0.250]*	0.930	0.352	0.001	63.469~	0.231
		Accuracy	10	480	0.178	[−0.022; 0.378]*	1.745	0.081	0.001	68.398~	0.248
	Attention - Divided Attention	Speed	6	307	−0.010	[−0.142; 0.122]	−0.151	0.888	0.382	5430	0.041
		Accuracy	4	167	−0.089	[−0.354; 0.176]§	−0.660	0.510	0.096	52.629~	0.195
	Processing Speed - Simple Reaction Time Task	Speed	14	820	0.069	[−0.020; 0.159]	1.491	0.136	0.141	28,887	0.088
		Accuracy									
	Processing Speed - 2-Choice Reaction Time Task	Speed	9	401	−0.023	[−0.125; 0.079]	−0.445	0.657	0.633	0.000	0.000
		Accuracy	3	117	−0.063	[−0.376; 0.250]$	−0.394	0.693	0.066	63.144~	0.219
	Processing Speed - >2-Choice Reaction Time Task	Speed	7	544	−0.054	[−0.140; 0.033]	−1.210	0.226	0.820	0.000	0.000
		Accuracy	3	131	−0.129	[−0.298; 0.041]§	−1.486	0.137	0.385	0.000	0.000
	Processing Speed - Other Tasks	Speed	6	249	0.067	[−0.121; 0.256]*	0.700	0.484	0.151	38.183~	0.139
		Accuracy	5	354	0.036	[−0.080; 0.152]	0.605	0.545	0.926	0.000	0.000
	Working Memory - n-back Tasks										
	0-back Task	Speed	8	267	−0.032	[−0.149; 0.086]	−0.530	0.596	0.879	0.000	0.000
		Accuracy	8	267	0.060	[−0.057; 0.178]	1.007	0.314	0.998	0.000	0.000
	1-back Task	Speed	11	420	−0.090	[−0.184; 0.004]	−1.876	0.061	0.916	0.000	0.000
		Accuracy	9	283	0.005	[−0.109; 0.119]	0.092	0.927	0.899	0.000	0.000
	2-back Task	Speed	13	474	−0.044	[−0.132; 0.044]	−0.976	0.329	0.936	0.000	0.000
		Accuracy	10	313	−0.054	[−0.163; 0.054]	−0.983	0.326	0.876	0.000	0.000
	3-back Task	Speed	10	398	−0.018	[−0.114; 0.079]	−0.358	0.720	0.993	0.000	0.000
		Accuracy	7	237	0.027	[−0.097; 0.152]	0.428	0.669	0.962	0.000	0.000
	Working Memory - Mental Tracking	Speed									
		Accuracy	7	438	−0.047	[−0.146; 0.052]	−0.927	0.354	0.852	0.000	0.000
D2	Perception - Visual and Auditory Perception	Speed	2	84	−0.015	[−0.225; 0.195]§	−0.141	0.888	0.871	0.000	0.000
		Accuracy	4	137	0.035	[−0.129; 0.199]	0.419	0.675	0.631	0.000	0.000
D3	Memory - Verbal and Visual Memory	Speed	3	102	0.042	[−0.148; 0.231]*	0.432	0.666	0.993	0.000	0.000
		Accuracy	10	625	−0.087	[−0.376; 0.203]$	−0.585	0.558	0.000	85.150~	0.395
D4	Verbal Functions and Language Skills - Verbal Expression no MA possible										
D5	Construction and Motor Performance - Motor Skills	Speed	2	42	−0.919	[−3.093; 1.256]$	−0.828	0.408	0.000	95.782~	1.536
		Accuracy	3	109	0.228	[−0.007; 0.463]#	1.898	0.058	0.906	0.000	0.000

(*continued on next page*)

Table 2 (*continued*)

Domain	Subclass	outcome measure	n - studies	n - subjects	Hedges's g	95% CI	z	p	p	I^2	Tau
D6	Concept Formation and Reasoning - Reasoning	Speed	4	263	0.010	[−0.110; 0.129]	0.157	0.875	0.700	0.000	0.000
		Accuracy	2	100	0.051	[−0.142; 0.245]*	0.522	0.602	0.608	0.000	0.000
	Concept Formation and Reasoning - Mathematical Procedures	Speed	4	168	0.033	[−0.116; 0.181]	0.429	0.668	0.947	0.000	0.000
		Accuracy	5	253	0.232	[−0.121; 0.586]#	1.286	0.198	0.000	86.083~	0.377
		Code	*	a small positive effect cannot be ruled out because the 95% CI includes +0.2.							
			#	Hedges's g indicates an effect but a null effect cannot be ruled out (the 95% CI includes zero).							
			§	a small negative effect cannot be ruled out because the 95% CI includes −0.2.							
			$	a positive or negative effect cannot be ruled out because the 95% CI includes −0.2 and +0.2.							
			~	at least moderate heterogeneity ($I^2 > 30\%$).							

Abbreviations: D1 – D6 – Domain 1 – Domain 6.

3.9.1.1.3. Narrative synthesis. There is one accuracy-related outcome measure, which was not considered in the *meta*-analysis, because another outcome measure was already used from the same study. Hedges's g for this outcome measure from a 2nd tier study (Besset et al. 2005) indicated a small, but not significant, negative effect (Table 3).

3.9.1.1.4. Studies not in meta-analysis. One study, which was not included in the *meta*-analysis because it did not provide numerical values to calculate effect sizes (Edelstyn and Oldershaw 2002) (Table 4, Supplementary Data 11), investigated accuracy in two tests on *Attentional Capacity*. The authors observed a statistically significant effect in one of them, indicating that performance was facilitated following mobile phone exposure.

3.9.1.2. Attention - Concentration / Focused Attention. The subclass *Concentration / Focused Attention* of the cognitive domain *Orientation and Attention* was investigated in eight studies. Two did not provide data suitable to be included in the *meta*-analyses (Cinel et al. 2008 Exp. 2; Wilén et al. 2006) (Table 4, Supplementary Data 11). Three studies provided data for accuracy-related outcomes only (Besset et al. 2005; Schmid et al. 2005; Unterlechner et al. 2008), two studies provided data for speed-related outcomes only (Lowden et al. 2019; Vecsei et al. 2018), and one study provided data for both (Haarala et al. 2003b; 2004) (Supplementary Data 6, p. 2).

3.9.1.2.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Concentration / Focused Attention* (Hedges's g 0.005, 95 % CI [−0.171; 0.180], $I^2 = 6.6$ %; Table 2). Since heterogeneity was negligible, there was no need for subgroup analyses.

3.9.1.2.2. Meta-analysis of accuracy-related outcome measures. Results for accuracy-related outcome measures mostly reflect those for speed-related outcome measures (Hedges's g 0.097, 95 % CI [−0.049; 0.244], $I^2 = 0.0$ %; Table 2), except that the non-significant RF-EMF effect is accompanied by a 95 % CI that does not exclude a small positive effect, i.e., an increase of accuracy. There is no heterogeneity between studies, thus there was no need for subgroup analyses.

3.9.1.2.3. Narrative synthesis. Five studies (six reports) contributed 12 outcome measures, which could not be included in the *meta*-analyses (Besset et al. 2005; Haarala et al. 2003b; 2004; Schmid et al. 2005; Unterlechner et al. 2008; Vecsei et al. 2018) (Table 3). All effect measures were statistically not significant; the values ranged from −0.185 to 0.289. There are two outcome measures (one speed-related (Vecsei et al. 2018) and one accuracy-related (Besset et al. 2005)), which indicate a small, but non-significant positive effect (Hedges's g > 0.2).

3.9.1.2.4. Studies not in meta-analyses. The two studies, which could not be included in the *meta*-analyses because they did not provide numerical values to calculate effect sizes (Cinel et al. 2008 Exp. 2; Wilén et al. 2006) (Table 4, Supplementary Data 11), reported no statistically significant main RF-EMF effect on accuracy- and speed-related outcome measures.

3.9.1.3. Attention - Vigilance. The subclass *Vigilance* of the cognitive domain *Orientation and Attention* was investigated in 12 studies. Five did not provide data suitable to be included in the *meta*-analyses (Cinel et al. 2008 Exp. 1; Preece et al. 1999; 2005; Russo et al. 2006; Zentai et al. 2015) (Table 4, Supplementary Data 11). Six studies (eight reports) provided data for accuracy- and speed-related outcome measures (Eggert et al. 2015; Haarala et al. 2003b; 2004; 2005; 2007; Sauter et al. 2011; 2015; Unterlechner et al. 2008), one provided data only for speed-related outcome measures (Koivisto et al. 2000b).

3.9.1.3.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Vigilance* (Hedges's g 0.118, 95 % CI [−0.044; 0.279], $I^2 = 41.1$ %; Table 2). The upper limit of the 95 % CI indicates that a small positive effect, i.e., a faster reaction under RF-EMF exposure, cannot be completely ruled out. I^2 indicates a moderate heterogeneity (Figure S13.1 in Supplementary Data 13).

Subgroup analysis showed that excluding the only 3rd tier study, which is also the only single-blind study (Koivisto et al. 2000b), reduces I^2 to zero. Hedges's g decreases to 0.039, with a 95 % CI that makes a small effect unlikely (Supplementary Data 12). When the only study performed in children (Haarala et al. 2005) is excluded from *meta*-analysis, heterogeneity for the adult population is still moderate to substantial. When *meta*-analyses are performed separately for studies which include males and females (Haarala et al. 2003b; 2004; 2005; Koivisto et al. 2000b; Unterlechner et al. 2008), and those which included males only (Eggert et al. 2015; Haarala et al. 2007; Sauter et al. 2011; 2015), heterogeneity reduces to $I^2 = 0.0$ % for males. For studies which comprise both, males and females, heterogeneity increases to substantial. Subgroup analyses for other parameters were not possible, because there were not enough studies per subgroup or no studies for some subgroups (Supplementary Data 12).

3.9.1.3.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Vigilance* (Hedges's g 0.042, 95 % CI [−0.094; 0.178], $I^2 = 0.0$ %; Table 2). Since there was no heterogeneity between studies, there was no need for subgroup analyses.

3.9.1.3.3. Narrative synthesis. Three studies (four reports) contributed 15 outcome measures, which could not be included in the *meta*-analyses (Eggert et al. 2015; Sauter et al. 2011; 2015; Unterlechner et al. 2008) (Table 3). All effect measures were statistically non-significant, the values for single outcome measures, however, ranged from −0.349 to 0.333. There is one accuracy-related measure which indicates a small,

Table 3
Outcome measures not reported in *meta*-analyses – summary. Heterogeneity measures, Hedges's g and 95% confidence interval (CI) for speed- and accuracy-related outcome measures for domains and subclasses of cognitive performance under RF exposure as compared to sham exposure.

Domain	Subclass	Certainty assessment					Range of effect sizes					
							Lowest effect size			Highest effect size		
		No of studies	Design (Cross-over / Parallel-groups)	Risk of Bias	Outcome measures (Speed /Accuracy)	Statistically significant effect	Mean	95% CI	Tier	Mean	95% CI	Tier
D1	Attention - Attentional Capacity	1	0/1	1st tier: 0 2nd tier: 1 3rd tier: 0	1 (0/1)	0	−0.235 [−0.765 ; 0.296] - 2nd tier					
D1	Attention -Concentration / Focused Attention	5	4/1	1st tier: 1 2nd tier: 4 3rd tier: 0	12 (6/6)	0	−0.185	[−0.526 ; 0.156]	1st	0.289	[−0.235 ; 0.813]	2nd
D1	Attention - Vigilance	3	3/0	1st tier: 2 2nd tier: 1 3rd tier: 0	15 (10/5)	0	−0.349	[−0.708 ; 0.011]	1st	0.333	[−0.026 ; 0.692]	1st
D1	Attention - Selective Attention	8	7/1	1st tier: 2 2nd tier: 6 3rd tier: 0	14 (8/6)	0	−0.149	[−0.630 ; 0.332]	2nd	0.323	[−0.201 ; 0.848]	2nd
D1	Attention - Divided Attention	3	3/0	1st tier: 2 2nd tier: 1 3rd tier: 0	15 (10/5)	0	−0.297	[−0.653 ; 0.060]	1st	0.171	[−0.180 ; 0.523]	1st
D1	Processing Speed - > 2-Choice Rection Time Task	1	0/1	1st tier: 0 2nd tier: 0 3rd tier: 1	1 (1/0)	0	−0.036 [−0.103 ; 0.124] - 3rd tier study					
D1	Processing Speed - Other Tasks *	5	4/1	1st tier: 0 2nd tier: 4 3rd tier: 1	31 (21/10)	4	−0.241	[−0.714 ; 0.231]	2nd	1,142	[0.386 ; 1.897]	2nd
D1	Working Memory - Mental Tracking	3	2/1	1st tier: 2 2nd tier: 1 3rd tier: 0	7 (1/6)	0	0.000	[−0.521 ; 0.521]	2nd	0.320	[−0.008 ; 0.648]	1st
D2	Perception - Visual and Auditory Perception	4	4/0	1st tier: 1 2nd tier: 1 3rd tier: 2	16 (2/14)	0	−0.447	[−1.047 ; 0.152]	3rd	0.213	[−0.361 ; 0.788]	3rd
D3	Memory - Verbal and Visual Memory **	8	5/3	1st tier: 2 2nd tier: 4 3rd tier: 2	31 (7/24)	4	−0.281	[−0.637 ; 0.075]	1st	0.733	[−0.137 ; 1.603]	2nd

(*continued on next page*)

Table 3 (*continued*)

Domain	Subclass	Certainty assessment					Range of effect sizes					
							Lowest effect size			Highest effect size		
		No of studies	Design (Cross-over / Parallel-groups)	Risk of Bias	Outcome measures (Speed /Accuracy)	Statistically significant effect	Mean	95% CI	Tier	Mean	95% CI	Tier
D4	Verbal Functions and Language Skills - Verbal Expression	1	1/0	1st tier: 0 2nd tier: 0 3rd tier: 1	1 (1/0)	0	0.070 [−0.209 ; 0.349] - 3rd tier study					
D5	Construction and Motor Performance - Motor Skills	2	1/1	1st tier: 1 2nd tier: 1 3rd tier: 0	4 (0/4)	0	−0.023	[−0.544 ; 0.498]	2nd	0.252	[−0.102 ; 0.606]	1st
D6	Concept Formation and Reasoning	1	1/0	1st tier: 0 2nd tier: 0 3rd tier: 1	2 (0/2)	0	0.057	[−0.222 ; 0.336]	3rd	0.086	[−0.192 ; 0.365]	3rd

* The statistically signficant effects refer to a better performance in 4 outcome measures in a visual reaction time task in one 2nd tier study. ** The statistically signficant effects refer to a better performance in 4 outcome measures in memory tasks in two 3rd tier studies and one 1st tier study
Abbreviations: D1 – D6 – Domain 1 – Domain 6.

but non-significant negative effect, i.e., an impairment of accuracy in a vigilance task (Sauter et al. 2011), and another accuracy-related outcome measure indicating a small statistically non-significant positive RF-EMF effect on performance (Unterlechner et al. 2008). On the other hand, two of the speed-related outcome measures indicated a faster reaction under RF-EMF exposure with small, but not statistically significant effect sizes (Eggert et al. 2015; Sauter et al. 2015).

3.9.1.3.4. Studies not in meta-analyses. All five studies, which did not provide data for *meta*-analyses (Cinel et al. 2008 Exp. 1; Preece et al. 1999; 2005; Russo et al. 2006; Zentai et al. 2015) (Table 4, Supplementary Data 11), reported results both for speed- and accuracy-related outcome measures. None of the investigated outcome measures showed statistically significant main effects of RF-EMF exposure.

3.9.1.4. Attention - Selective Attention. The subclass *Selective Attention* of the cognitive domain *Orientation and Attention* was investigated in 25 studies. Eleven did not or only partly provide data suitable to be included in the *meta*-analyses (Table 4, Supplementary Data 11). Seven studies (eight reports) provided data for both accuracy- and speed-related outcome measures (Curcio et al. 2004; Eggert et al. 2015; Hamblin et al. 2004; Kleinlogel et al. 2008; Sauter et al. 2011; 2015; Schmid et al. 2005; Unterlechner et al. 2008), six (seven reports) provided data only for speed-related outcome measures (Curcio et al. 2012; Hamblin et al. 2006; Jech et al. 2001; Regel et al. 2006; Trunk et al. 2014; 2015; Vecchio et al. 2012), and three only for accuracy-related outcome measures (Besset et al. 2005; Fritzer et al. 2007; Malek et al. 2015).

3.9.1.4.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Selective Attention* (Hedges's g 0.080, 95 % CI [−0.089; 0.250], I^2 = 63.5 %; Table 2). However, the 95 % CI of Hedges's g indicates that a small positive effect, i.e., a faster reaction under RF-EMF exposure, cannot be completely ruled out. I^2 indicates a moderate to considerable heterogeneity (Table 2, Figure 13.2 Supplementary Data 13).

Subgroup analysis for speed-related outcome measures revealed that excluding the only 3rd tier study, which was also the only single-blind study (Hamblin et al. 2004), reduced I^2 to 0.0 %. Subgroup analyses reduced I^2 to zero and Hedges's g decreased to 0.023 with a 95 % CI that makes a small effect unlikely [−0.081; 0.128] when only large sample studies were included (Eggert et al. 2015; Hamblin et al. 2006; Regel et al. 2006; Sauter et al. 2011; 2015; Schmid et al. 2005; Unterlechner et al. 2008). Heterogeneity remained moderate to substantial for studies which included only adults without IEI and patients (n = 11 studies), both sexes (n = 9 studies) or only males (Curcio et al. 2012; Eggert et al. 2015; Kleinlogel et al. 2008; Sauter et al. 2011; 2015), only head exposure (n = 12 studies), and for those which had a mixed or governmental funding (n = 11 studies). There were no parallel-group studies and no studies with children and/or adolescents (Supplementary Data 12).

3.9.1.4.2. Meta-analysis of accuracy-related outcome measures. The results of the *meta*-analysis for accuracy-related measures are similar (Hedges's g 0.178, 95 % CI [−0.022; 0.378], I^2 = 68.4 %; Table 2). They do not indicate a statistically significant effect. However, the 95 % CI indicates that a higher accuracy under RF-EMF exposure cannot completely be ruled out. I^2 indicates a moderate to considerable heterogeneity (Table 2, Figure 13.3 in Supplementary Data 13).

Subgroup analyses for accuracy-related outcome measures revealed that heterogeneity decreased to zero when only cross-over studies (n = 8 studies) were considered. Hedges's g decreased to 0.097 with a 95 % CI, which makes even a slight effect unlikely [0.000; 0.193]. Heterogeneity remained moderate to substantial for 1st and 2nd tier studies (n = 8 studies), parallel-group studies (Besset et al. 2005; Fritzer et al. 2007), studies with small (Curcio et al. 2004; Fritzer et al. 2007; Hamblin et al. 2004; Kleinlogel et al. 2008) or large sample sizes (Besset et al. 2005; Eggert et al. 2015; Malek et al. 2015; Sauter et al. 2011; 2015; Schmid et al. 2005; Unterlechner et al. 2008), adults without IEI (and patients) (n = 9 studies), studies including both sexes (Besset et al. 2005; Curcio et al. 2004; Hamblin et al. 2004; Malek et al. 2015; Schmid et al. 2005; Unterlechner et al. 2008) or solely men (Eggert et al. 2015; Fritzer et al. 2007; Kleinlogel et al. 2008; Sauter et al. 2011; 2015), studies with head exposure (n = 9 studies), studies with governmental or mixed funding (n = 9 studies), and double-blind studies (n = 7 studies). There is no study on children and/or adolescents (Supplementary Data 12).

3.9.1.4.3. Narrative synthesis. Eight studies contributed 14 outcome measures, which could not be included in the *meta*-analyses because

Table 4
Summary of results of studies not providing data for *meta*-analyses.

Domain	Subclass	No of studies	Design (Cross-over / Parallel-groups)	Risk of Bias	Number of participants	Outcome measures (Speed / Accuracy)	Statistically significant effect	Effect of EMF
D1	Attention – Attentional Capacity	1	0/1	1st tier: 0 2nd tier: 0 3rd tier: 1	38	2 (0/2)	1	improvement of accuracy in one task
D1	Attention – Concentration / Focused Attention	2	2/0	1st tier: 0 2nd tier: 1 3rd tier: 1	208	5 (2/3)	2	main effect not statistically significant, interaction with Stroop Test version: improvement of speed and accuracy in the 2nd tier study; see Supplementary Data 11
D1	Attention – Vigilance	5	5/0	1st tier: 1 2nd tier: 4 3rd tier: 0	405	16 (10/6)	0	
D1	Attention – Selective Attention	11	11/0	1st tier: 3 2nd tier: 7 3rd tier: 1	786	29 (12/17)	0	
D1	Attention – Divided Attention	2	2/0	1st tier: 1 2nd tier: 1 3rd tier: 0	133	3 (3/0)	0	
D1	Processing Speed – Simple Reaction Time Task	5	5/0	1st tier: 1 2nd tier: 4 3rd tier: 0	262	6 (5/1)	3	increased speed in two studies (1st tier and 2nd tier) 1st tier not statistically significant after Bonferroni correction
D1	Processing Speed – 2-Choice Reaction Time Task	8	8/0	1st tier: 4 2nd tier: 3 3rd tier: 1	300	13 (6/7)	2	increased speed in in one 2nd tier study, decreased speed in one 3rd tier study
D1	Processing Speed – > 2-Choice Reaction Time Task	3	3/0	1st tier: 1 2nd tier: 2 3rd tier: 0	301	8 (7/1)	0	
D1	Processing Speed – Other Tasks	3	3/0	1st tier: 0 2nd tier: 0 3rd tier: 3	63	7 (2/5)	0	
D1	Working Memory – 0-back Task	1	1/0	1st tier: 0 2nd tier: 1 3rd tier: 0	10	2 (1/1)	0	
D1	Working Memory – 1-back Task	8	8/0	1st tier: 3 2nd tier: 5 3rd tier: 0	335	16 (7/9)	2	reduced accuracy in adolescents in one 2nd tier study (individually adapted difficulty level) and reduced accuracy before correction for multiple testing in adults in one 1st tier study
D1	Working Memory – 2-back Task	7	7/0	1st tier: 2 2nd tier: 5 3rd tier: 0	463	17 (7/10)	1	reduced accuracy in adolescents in one 2nd tier study (individually adapted difficulty level)
D1	Working Memory – 3-back Task	7	7/0	1st tier: 2 2nd tier: 5 3rd tier: 0	463	17 (7/10)	2	reduced accuracy in adolescents in one 2nd tier study (individually adapted difficulty level)and in adults in a 1st tier study
D1	Working Memory – Mental Tracking	5	4/1	1st tier: 1 2nd tier: 2 3rd tier: 2	185	17 (5/12)	2	accuracy facilitated in one 3rd tier study
D2	Perception – Visual and Auditory Perception	5	5/0	1st tier: 0 2nd tier: 4 3rd tier: 1	278	6	2	auditory order threshold negatively affected in two 2nd tier studies
D3	Memory – Verbal and Visual Memory	7	5/2	1st tier: 2 2nd tier: 2 3rd tier: 3	438	19 (14/15)	1	decreased speed in one 3rd tier study
D4	Verbal Functions and Language Skills – Verbal Expression	1	0/1	1st tier: 0 2nd tier: 0 3rd tier: 1	48	1 (0/1)	0	
D6	Conecept Formation and Reasoning – Mathematical Procedures	1	1/0	1st tier: 0 2nd tier: 1 3rd tier: 0	168	2 (1/1)	0	

Study characteristics, number and direction of effects of studies providing no or only partly data to be considered in *meta*-analyses.
Abbreviations: CI – Confidence Interval, D1 – D6 – Domain 1- Domain 6, EMF – electromagnetic field.

they used additional tests (Table 3). The values of Hedges's g for single outcome measures, however, ranged from −0.149 to 0.323. Two of the speed- (Jech et al. 2001; Trunk et al. 2015) and two of the accuracy-related (both Besset et al. 2005) outcome measures show a small effect (Hedges's g > 0.2) in the direction of faster reaction and a higher accuracy under exposure, respectively. However, effect measures were statistically not significant, i.e., all 95 % CIs included 0.

3.9.1.4.4. Studies not in meta-analyses. Of the nine studies, which did not provide data for *meta*-analyses, five reported results both for speed- and accuracy-related outcome measures (Cinel et al. 2008 Exp. 2; Kwon et al. 2011; 2012; Leung et al. 2011; Preece et al. 2005), one reported results for accuracy-related outcome measures only (Stefanics et al. 2008), one covered only speed-related outcome measures (Eliyahu et al. 2006), and two studies did not report on accuracy-related measures in the main results due to unequal parallel versions of their applied test in one study (Wallace et al. 2012), and to problems with appropriate data due to ceiling and flooring effects in the other study (Riddervold et al. 2008). Two more studies, which provided speed data for the *meta*-analyses, did not report data of their accuracy-related outcome measures (Jech et al. 2001; Regel et al. 2006). None of the investigated outcome measures were statistically significantly affected by RF-EMF exposure (Table 4, Supplementary Data 11).

3.9.1.5. Attention - Divided Attention. The subclass *Divided Attention* of the cognitive domain *Orientation and Attention* was investigated in eight studies. Two did not provide data suitable to be included in the *meta*-analyses (Riddervold et al. 2008; 2010) (Supplementary Data 6). Four studies (five reports) provided data for both accuracy- and speed-related outcome measures (Eggert et al. 2015; Lass et al. 2002; Sauter et al. 2011; 2015; Unterlechner et al. 2008), while two provided data only for speed-related outcome measures (Fritzer et al. 2007; Keetley et al. 2006).

3.9.1.5.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Divided Attention* (Hedges's g −0.010, 95 % CI [−0.142; 0.122], $I^2 = 5.4$ %; Table 2). Since heterogeneity was low, there was no need for subgroup analyses.

3.9.1.5.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures show no statistically significant effect of RF-EMF exposure on this outcome measure (Hedges's g −0.089, 95 % CI [−0.354; 0.176]. $I^2 = 52.6$ %; Table 2). However, the 95 % CI indicates that a small negative effect, i.e., a lower accuracy under RF-EMF exposure cannot completely be ruled out. Heterogeneity of studies was moderate (Figure 13.4 in Supplementary Data 13).

A subgroup analysis for accuracy-related outcome measures revealed that restricting the analysis to the three 1st and 2nd tier studies (four reports) (Eggert et al. 2015; Sauter et al. 2011; 2015; Unterlechner et al. 2008) (e.g. not considering Lass et al. 2002) reduced I^2 to 32.5 %, which might not be important or represent moderate heterogeneity. Since Lass et al. (2002) was the only 3rd tier study and also the only single-blind and parallel-group design study, results are the same when only cross-over and double-blind studies are considered. When only studies with male samples are analysed (Eggert et al. 2015; Sauter et al. 2011; 2015), I^2 reduced to zero, while for studies which included males and females (Lass et al. 2002; Unterlechner et al. 2008) I^2 increased to a substantial to considerable heterogeneity. All four studies were small studies, did neither include subjects with IEI nor children and/or adolescents, used head exposure, and had a governmental or mixed funding, so subgroup analyses for these factors were not possible (Supplementary Data 12).

3.9.1.5.3. Narrative synthesis. Three studies (four reports) (Eggert et al. 2015; Sauter et al. 2011; 2015; Unterlechner et al. 2008) contributed 15 outcome measurements additional to the ones included in the *meta*-analyses (Table 3). The values of Hedges's g for single outcome measurements ranged from −0.297 to 0.171. The small negative effect indicates a lower accuracy under exposure. However, this effect measure was not significant, since the 95 % CI included 0.

3.9.1.5.4. Studies not in meta-analyses. Two reports (Riddervold et al. 2008; 2010), which did not provide data for *meta*-analyses, reported results for speed-related outcome measures, both of which were not affected by RF-EMF exposure (Table 4, Supplementary Data 11).

3.9.1.6. Processing Speed - Simple Reaction Time Task. The subclass *Processing Speed / Simple Reaction Time Task* of the cognitive domain *Orientation and Attention* was investigated in 21 studies of which 14 provided information to be used in the *meta*-analyses of speed-related outcome measures (Supplementary Data 6).

3.9.1.6.1. Meta-analysis of speed-related outcome measures. The result of the *meta*-analysis did not indicate a statistically significant effect of RF-EMF exposure on *Simple Reaction Time* (Hedges's g 0.069, 95 % CI [−0.020; 0.159], $I^2 = 28.9$ %; Table 2). Since heterogeneity as assessed by I^2 was low, there was no need for subgroup analyses.

3.9.1.6.2. Meta-analysis of accuracy-related outcome measures. No study reported accuracy-related outcome measures.

3.9.1.6.3. Narrative synthesis. There is no outcome measure, which could not be considered in the *meta*-analysis.

3.9.1.6.4. Studies not in meta-analysis. Five studies did not contribute numerical values for a *meta*-analysis (Preece et al. 1999; 2005; Regel et al. 2007b; Russo et al. 2006; Schmid et al. 2012b) (Supplementary Data 6 p. 9, Table 4, Supplementary Data 11); RF-EMF exposure did not significantly affect performance in three studies (Preece et al. 1999; Regel et al. 2007b; Russo et al. 2006); and in two studies a favourable effect, resulting in increased speed, was observed (Preece et al. 2005; Schmid et al. 2012b) (Supplementary Data 6 p. 9). However, in one of these studies the effect disappeared after correction for multiple testing (Preece et al. 2005). In two studies (Riddervold et al. 2008; 2010) a simple reaction time task was performed according to the methods section, but no results were reported.

3.9.1.7. Processing Speed - Two-Choice Reaction Time Task. The subclass *Processing Speed – 2-Choice Reaction Time Task* of the cognitive domain *Orientation and Attention* was investigated in 14 studies. Eight studies did not or did only partly provide data suitable to be included in the *meta*-analyses (Supplementary Data 6). Three studies provided data for both accuracy- and speed-related outcome measures (Haarala et al. 2003b; 2004; 2005; Loughran et al. 2013), while six provided data only for speed-related outcome measures (Besset et al. 2005; Curcio et al. 2004; Koivisto et al. 2000b; Regel et al. 2006; 2007b; Schmid et al. 2012a).

3.9.1.7.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures (Hedges's g −0.023, 95 % CI [−0.125; 0.079], $I^2 = 0.0$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on *2-Choice-Reaction Time*. Since there was no heterogeneity, there was no need for subgroup analyses.

3.9.1.7.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures (Hedges's g −0.063, 95 % CI [−0.376; 0.250], $I^2 = 63.1$ %, Table 2) showed no statistically significant effect of RF-EMF exposure on this outcome measure. The 95 % CI of Hedges's g, however, showed that neither a small negative nor a small positive effect can completely be ruled out. Heterogeneity of studies was moderate to substantial (Figure 13.5 in Supplementary Data 13).

A subgroup analysis of accuracy-related outcome measures revealed that all three studies (four reports) (Haarala et al. 2003b; 2004; 2005; Loughran et al. 2013) were 1st tier cross-over studies, did not follow a parallel-group design, did not include subjects with IEI, used head exposure, and received a governmental or mixed funding. Excluding one study with a small sample (Loughran et al. 2013) even increased heterogeneity to a substantial / considerable level. Restricting the *meta*-analysis to the two studies in children and/or adolescents (Haarala et al. 2005; Loughran et al. 2013) removed heterogeneity completely (Supplementary Data 12).

3.9.1.7.3. Narrative synthesis. None of the studies contributed further outcome measures, which could not be included in the *meta*-analyses (Supplementary Data 6).

3.9.1.7.4. Studies not in meta-analyses. Four reports, which did not provide data for *meta*-analyses, reported results for speed- and accuracy-related outcome measures (Preece et al. 1999; 2005; Regel et al. 2007a; Schmid et al. 2012b), while one contributed information for a speed-related outcome measure only (Eliyahu et al. 2006). In three additional studies, speed data were analysed in the *meta*-analyses (Regel et al. 2006; 2007b; Schmid et al. 2012a), whereas accuracy data were not reported with sufficient detail. Speed was not affected by RF-EMF exposure in three studies (Preece et al. 2005; Regel et al. 2007a; Schmid et al. 2012b). In one 2nd tier study (Preece et al. 1999) an increase of reaction time was observed, whereas in one 3rd tier study

(Eliyahu et al. 2006) left hand responses slowed down under left side exposure. Right side exposure and sham exposure led to an acceleration of speed, right hand responses were not affected. Accuracy was not affected by RF-EMF exposure in any of the seven studies (Table 4, Supplementary Data 11).

3.9.1.8. Processing Speed - More than 2-Choice Reaction Time Task. The subclass *Processing Speed – >2-Choice Reaction Time Task* of the cognitive domain *Orientation and Attention* was investigated in 10 studies. Three did not provide data suitable to be included in the *meta*-analyses (Riddervold et al. 2008; 2010; Russo et al. 2006) (Supplementary Data 6). Three studies (four reports) provided data for both accuracy- and speed-related outcome measures (Haarala et al. 2003b; 2004; 2005; 2007), while four provided data only for speed-related outcome measures (Besset et al. 2005; Keetley et al. 2006; Koivisto et al. 2000b; Malek et al. 2015).

3.9.1.8.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures (Hedges's g −0.054, 95 % CI [−0.140; 0.033], $I^2 = 0.0$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on > *2-Choice-Reaction-Time*. Since there was no heterogeneity, there was no need for subgroup analyses.

3.9.1.8.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures (Hedges's g −0.129, 95 % CI [−0.298; 0.041], $I^2 = 0.0$ %; Table 2) also showed no statistically significant effect of RF-EMF exposure on this outcome measure. The 95 % CI of Hedges's g, however, showed that a small negative effect, i.e., a lower accuracy, cannot completely be ruled out. There was no heterogeneity between studies.

3.9.1.8.3. Narrative synthesis. One of the studies (Malek et al. 2015) contributed a second speed-related outcome measure, which could not be included in the *meta*-analyses (Table 3). In line with the results from the *meta*-analysis, Hedges's g indicates that there is no statistically significant effect.

3.9.1.8.4. Studies not in meta-analyses. One study, which did not provide data for *meta*-analyses, reported results for speed- and accuracy-related outcome measures (Russo et al. 2006), while two additional studies contributed information for speed-related outcome measures only (Riddervold et al. 2008; 2010). None of the results revealed a statistically significant effect of RF-EMF exposure on performance in a *Choice Reaction Time Task* with more than two choices.

3.9.1.9. Processing Speed – Other Tasks. The subclass *Processing Speed – Other Tasks* of the cognitive domain *Orientation and Attention* was investigated in 11 studies. Three did not provide data suitable to be included in the *meta*-analyses (Freude et al. 1998; 2000; Meister et al. 1989) (Supplementary Data 6). Three studies (four reports) provided data for both accuracy- and speed-related outcome measures (Eggert et al. 2015; Keetley et al. 2006; Sauter et al. 2015; Terao et al. 2006), while three provided data only for speed- (Fritzer et al. 2007; Furubayashi et al. 2009; Terao et al. 2007) and two only for accuracy-related outcome measures (Eltiti et al. 2009; Lass et al. 2002).

3.9.1.9.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures (Hedges's g 0.067, 95 % CI [−0.121; 0.256], $I^2 = 38.2$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on *Processing Speed – Other Tasks*, but the CI indicates that a small positive effect cannot be ruled out. Since heterogeneity as assessed by I^2 was moderate (Figure 13.6 in Supplementary Data 13), a subgroup analysis was performed.

The results of the subgroup analysis (Supplementary Data 12) revealed that I^2 reduces to zero when only studies based on large samples are included (Eggert et al. 2015; Furubayashi et al. 2009; Keetley et al. 2006; Sauter et al. 2015). Heterogeneity remained moderate to substantial for cross-over-studies (Eggert et al. 2015; Furubayashi et al. 2009; Keetley et al. 2006; Sauter et al. 2015; Terao et al. 2006; 2007), small studies (Fritzer et al. 2007; Terao et al. 2006; 2007), studies on adults without IEI (Eggert et al. 2015; Fritzer et al. 2007; Keetley et al. 2006; Sauter et al. 2015; Terao et al. 2006; 2007), studies including both sexes (Keetley et al. 2006; Terao et al. 2006; 2007) or solely men (Eggert et al. 2015; Fritzer et al. 2007; Sauter et al. 2015), studies with head exposure (Eggert et al. 2015; Fritzer et al. 2007; Keetley et al. 2006; Sauter et al. 2015; Terao et al. 2006; 2007), and double-blind studies (Eggert et al. 2015; Furubayashi et al. 2009; Keetley et al. 2006; Sauter et al. 2015; Terao et al. 2006; 2007). There were no 3rd tier studies, no studies including children and/or adolescents, and all studies had a governmental or mixed funding, hence, no subgroup analysis was possible for these factors.

3.9.1.9.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures showed no statistically significant effect of RF-EMF exposure on this outcome measure (Hedges's g 0.036, 95 % CI [−0.080; 0.152], $I^2 = 0.0$ %; Table 2). There was no heterogeneity between studies.

3.9.1.9.3. Narrative synthesis. Five studies contributed another 31 outcome measures, which could not be included in the *meta*-analyses (Furubayashi et al. 2009; Keetley et al. 2006; Lass et al. 2002; Terao et al. 2006; 2007) (Table 3). Of these, 21 were speed-related outcome measures, and 10 were accuracy-related outcome measures. Three of the outcome measures (one accuracy- and two speed-related, all Terao et al. (2006)) indicated a small negative effect of RF-EMF exposure, i.e., a longer reaction time or a lower accuracy, respectively, with effect sizes between −0.205 and −0.241. On the other hand, seven of the outcome measures indicated a faster reaction time under RF-EMF exposure with effect sizes up to 1.142 (all from the same study, Terao et al. (2007)); four of those effects were significant, i.e., the 95 % CI did not include 0; and one accuracy-related outcome measure (Terao et al. 2006) indicated a higher accuracy under RF-EMF exposure, which was not significant.

3.9.1.9.4. Studies not in meta-analyses. Three studies, which did not provide data for *meta*-analyses (Freude et al. 1998; 2000; Meister et al. 1989), reported results for speed- and/or accuracy-related outcome measures. None of them indicated a statistically significant effect of RF-EMF on the specific tasks (Table 4, Supplementary Data 11).

3.9.1.10. Working Memory - n-back Tasks. The subclass *Working Memory – n-back Tasks* of the cognitive domain *Orientation and Attention* was investigated at levels of difficulty from 0-back tasks to 3-back tasks. The number of studies investigating speed-related outcome measures varies from eight for 0-back tasks to 13 for 2-back tasks. The number of studies investigating accuracy-related outcome measures varies from seven for 3-back tasks to 10 for 2-back tasks.

3.9.1.10.1. Meta-analyses of speed- and accuracy-related outcome measures. Neither for speed- nor for accuracy-related outcome measures *meta*-analyses revealed a significant effect of RF-EMF exposure (Hedges's g ranging from −0.090 [−0.184; 0.004] to 0.060 [−0.057; 0.178], all $I^2 = 0.0$ %; Table 2). This applied to all levels of difficulty. For all levels of difficulty, as well as for both speed- and accuracy-related outcome measures, there was no heterogeneity between studies, thus no subgroup analyses were performed.

3.9.1.10.2. Narrative synthesis. There is no outcome measure, which could not be considered in the *meta*-analysis.

3.9.1.10.3. Studies not in meta-analyses. Six of the nine studies, which did not or only partly provide data suitable for *meta*-analyses (Aalto et al. 2006; Cinel et al. 2008 Exp. 1; Haarala et al. 2003a; Regel et al. 2007a; 2007b; Schmid et al. 2012b), confirm the results for no effect of RF-EMF exposure in any of their applied levels of the *n-back Tasks* (Table 4, Supplementary Data 11). In two studies accuracy was statistically significantly affected by RF-EMF exposure in only one of three applied difficulty levels each. In one of them (Schmid et al. 2012a) accuracy decreased statistically significantly in adults in the first session of a *3-back Task* in a 14 Hz-pulse-modulated condition only. No further effects were observed in two other levels or speed-related outcome measures or with other pulse-modulation frequencies (2 Hz, 8 Hz, 217 Hz and combinations) in that study. In the other study (Regel et al. 2006) accuracy decreased in non-sensitive participants only in the first session of the *1-back Task*. This result was no longer statistically significant after correction for multiple testing. There was only one study (Leung et al. 2011), in which accuracy was statistically significantly higher in the sham than in the 3G exposure condition in an n-back version with adjusted difficulty levels (1-, 2- or 3-back) according to individual performance. The effect was observed in adolescents only; accuracy of young adults and elderly participants in the *n-back Tasks* was not affected, and no statistically significant effect was observed in the 2G condition.

3.9.1.11. Working Memory - Mental Tracking. The subclass *Working Memory – Mental Tracking* of the cognitive domain *Orientation and Attention* was investigated in 12 studies. Five did not provide data suitable to be included in the *meta*-analyses (Edelstyn and Oldershaw 2002; Preece et al. 1999; 2005; Riddervold et al. 2010; Wilén et al. 2006) (Supplementary Data 6). The remaining seven studies (eight reports) all provided data for accuracy-related outcome measures only (Besset et al. 2005; Fritzer et al. 2007; Hosseini et al. 2019; Keetley et al. 2006; Papageorgiou et al. 2004; 2006; Verrender et al. 2016; Wallace et al. 2012).

3.9.1.11.1. Meta-analysis of speed-related outcome measures. There were no studies reporting speed-related outcome measures.

3.9.1.11.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis (Hedges's g −0.047, 95 % CI [−0.146; 0.052], $I^2 = 0.0$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on *Mental Tracking*. Since there was no heterogeneity, there was no need for subgroup analyses.

3.9.1.11.3. Narrative synthesis. Three of the seven studies contributed seven additional accuracy-related outcome measures, which could not be included in the *meta*-analyses (Besset et al. 2005; Verrender et al. 2016; Wallace et al. 2012) (Table 3). Although Hedges's g indicated a small positive effect of RF-EMF exposure for one accuracy-related outcome measure (i.e., a higher accuracy in Besset et al. (2005)) and for one speed-related measure (i.e., faster reaction in Verrender et al. (2016)), none of the effect sizes was statistically significant.

3.9.1.11.4. Studies not in meta-analyses. Three studies with in total five tasks (Preece et al. 1999; 2005; Wilén et al. 2006), which did not provide data for *meta*-analyses, reported results for speed- and accuracy-related outcome measures, while two additional studies on another five tasks (Edelstyn and Oldershaw 2002; Riddervold et al. 2010) contributed information for accuracy-related outcome measures only (Table 4, Supplementary Data 11). Speed-related outcome measures were not affected by RF-EMF exposure in any of these additional studies, whereas in one 3rd tier study (Edelstyn and Oldershaw 2002) accuracy of *Mental Tracking* was facilitated.

3.9.2. Domain 2 Perception

3.9.2.1. Visual and Auditory Perception. The subclass *Visual and Auditory Perception* of the cognitive domain *Perception* was investigated in nine studies. Four (five reports) did not provide data suitable to be included in the *meta*-analyses (Cinel et al. 2007; Maier 2001; Maier et al. 2004a; 2004b; Meister et al. 1989) (Supplementary Data 6). Of the remaining five studies, three reported data for accuracy-related outcome measures only (Irlenbusch et al. 2007; Rodina et al. 2005; Schmid et al. 2005), one reported data for speed-related data only (Koivisto et al. 2000b), and one reported data for both (Verrender et al. 2016).

3.9.2.1.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures (Hedges's g −0.015, 95 % CI [−0.225; 0.195], $I^2 = 0.0$ %; Table 2) do not indicate a significant effect of RF-EMF exposure. However, the 95 % CI indicates that a small negative effect, i.e., a slower reaction under RF-EMF exposure, cannot completely be ruled out.

3.9.2.1.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures (Hedges's g 0.035, 95 % CI [−0.129; 0.199], $I^2 = 0.0$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on *Visual and Auditory Perception*.

Since there was no heterogeneity neither for speed- nor for accuracy-related outcome measures, there was no need for subgroup analyses.

3.9.2.1.3. Narrative synthesis. Four studies contributed 16 additional outcome measures, which could not be included in the *meta*-analyses (Koivisto et al. 2000b; Rodina et al. 2005; Schmid et al. 2005; Verrender et al. 2016) (Table 3). For two of the accuracy-related outcome measures a small, but not statistically significant effect, was observed (both Rodina et al. 2005). One indicated a lower accuracy under RF-EMF exposure (−0.447) and one a higher accuracy (0.213).

3.9.2.1.4. Studies not in meta-analyses. Four studies (five reports) did not provide any data for *meta*-analyses (Cinel et al. 2007; Maier 2001; Maier et al. 2004a; 2004b; Meister et al. 1989), an additional one did not provide data for one task (Schmid et al. 2005) (Table 4, Supplementary Data 11). The data of these studies refer to perception threshold, order threshold, or contrast threshold as outcome measures. In two studies (three reports) of the same research group the auditory order threshold was negatively affected by RF-EMF exposure (Maier 2001; Maier et al. 2004a; 2004b). Another research group could not replicate their finding (Cinel et al. 2007). In one study on visual contrast sensitivity no RF-EMF effect was observed (Schmid et al. 2005); in another visual perception task results remained unclear due to insufficient data provided (Meister et al. 1989).

3.9.3. Domain 3 Memory

3.9.3.1. Verbal and Visual Memory. The subclass *Verbal and Visual Memory* of the cognitive domain *Memory* was investigated in 20 studies. Seven studies did not provide data suitable to be included in the *meta*-analyses (Cinel et al. 2008 Exp. 2; Eibert et al. 1997; Eliyahu et al. 2006; Luria et al. 2009; Preece et al. 1999; 2005; Riddervold et al. 2008) (Table 4, Supplementary Data 11). Ten studies provided data for accuracy-related outcome measures only (Besset et al. 2005; Bueno-Lopez et al. 2021; Fritzer et al. 2007; Keetley et al. 2006; Krause et al. 2000b; 2004; 2007; Lass et al. 2002; Malek et al. 2015; Movvahedi et al. 2014); two studies provided data for speed-related outcome measures only (Koivisto et al. 2000b; Wiholm et al. 2009); and one study provided data for both (Hinrichs and Heinze 2004). Of these 10 studies, only nine were considered in the *meta*-analysis, since for one study (Movvahedi et al. 2014) neither the name of the performance task nor the reported "memory score" was specified; this result was considered for the narrative review only.

3.9.3.1.1. Meta-analysis of speed-related outcome measures. The results of the *meta*-analysis for speed-related outcome measures (Hedges's g 0.042, 95 % CI [−0.148; 0.231], $I^2 = 0.0$ %; Table 2) do not indicate a statistically significant effect of RF-EMF exposure on *Verbal and Visual Memory*. The 95 % CI indicates that a possible small positive effect, i.e., an increase of speed under RF-EMF exposure, cannot be completely ruled out. Since heterogeneity was negligible, there was no need for subgroup analyses.

3.9.3.1.2. Meta-analysis of accuracy-related outcome measures. The result of the *meta*-analysis of accuracy-related outcome measures is non-significant (Hedges's g −0.087, 95 % CI [−0.376; 0.203], $I^2 = 85.2$ %; Table 2), but the 95 % CI indicates that both a small positive or negative effect, i.e., a decrease or an increase of accuracy, cannot be ruled out. The heterogeneity was substantial to considerable.

The subgroup analyses for accuracy-related outcome measures (Supplementary Data 12) revealed that for 3rd tier studies (Krause et al. 2000a; Lass et al. 2002; Malek et al. 2015) the I^2 dropped to zero, while for 1st and 2nd tier studies I^2 even slightly increased. Heterogeneity increased to "considerably" when *meta*-analysis was performed separately for cross-over studies (Bueno-Lopez et al. 2021; Hinrichs and Heinze 2004; Keetley et al. 2006; Krause et al. 2000a; 2004; 2007). For parallel-group studies (Besset et al. 2005; Fritzer et al. 2007; Lass et al. 2002; Malek et al. 2015), I^2 decreased to 16.5 %, which indicated a non-important heterogeneity. For large sample studies (Besset et al. 2005; Bueno-Lopez et al. 2021; Keetley et al. 2006; Krause et al. 2007; Lass et al. 2002; Malek et al. 2015), heterogeneity decreased, but still was substantial. Heterogeneity did not change notably for small sample studies (Fritzer et al. 2007; Hinrichs and Heinze 2004; Krause et al. 2000a; 2004). When the only study, which included IEI subjects, which is also the only study representing whole body exposure (Malek et al. 2015), was excluded from the *meta*-analysis, heterogeneity did not change notably. When *meta*-analyses were performed for males (Bueno-Lopez et al. 2021; Fritzer et al. 2007; Krause et al. 2007) and both sexes (Besset et al. 2005; Hinrichs and Heinze 2004; Keetley et al. 2006; Krause et al. 2000a; 2004; Lass et al. 2002; Malek et al. 2015) separately, both I^2 values still indicated a substantial heterogeneity. However, as seen before, heterogeneity is lower for studies with males only ($I^2 =$ 61.1 %) as compared to studies which included males and females ($I^2 =$ 89.1 %). Since there were no studies with children and/or adolescents, this factor could not be considered for a subgroup analysis.

3.9.3.1.3. Narrative synthesis. Additional data from eight studies with in total 31 outcome measures not included in *meta*-analyses (Besset et al. 2005; Bueno-Lopez et al. 2021; Fritzer et al. 2007; Hinrichs and Heinze 2004; Keetley et al. 2006; Lass et al. 2002; Malek et al. 2015; Wiholm et al. 2009) indicated better performance in four outcome measures in two 3rd tier studies (Lass et al. 2002; Malek et al. 2015) and one 1st tier study (Wiholm et al. 2009) (Table 3). Movvahedi et al. (2014) reported improvement in talk mode compared to sham in an undefined memory score.

3.9.3.1.4. Studies not in meta-analyses. Additional data from seven studies providing no values for *meta*-analyses (see above, Table 4, Supplementary Data 11) indicated reduced speed in one 3rd tier study (Eliyahu et al. 2006).

3.9.4. Domain 4 Verbal Functions and Language Skills

3.9.4.1. Verbal Expression. The subclass *Verbal Expression* of the cognitive domain *Verbal Functions and Language Skills* was investigated in two 3rd tier studies, of which only one provided numerical data (Koivisto et al. 2000b). Thus, a *meta*-analysis for this domain could not be performed. Hedges's g for the speed-related outcome measure was 0.070 (95 % CI [−0.209; 0.349]) and did not indicate a significant effect of RF-EMF exposure. Accuracy was also not affected in the other study that does not provide numerical data (Edelstyn and Oldershaw 2002).

3.9.5. Domain 5 Construction and Motor Performance

3.9.5.1. Motor Skills. The subclass *Motor Skills* of the cognitive domain *Construction and Motor Performance* was investigated in four studies (Supplementary Data 6). One reported data for both accuracy- and speed-related outcome measures (Curcio et al. 2008); two reported data for accuracy-related outcome measures only (Besset et al. 2005; Bueno-Lopez et al. 2021); and one for speed-related outcome measures only (Lustenberger et al. 2013).

3.9.5.1.1. Meta-analysis of speed-related outcome measures. The results of the *meta*-analysis for speed-related outcome measures (Hedges's g −0.919, 95 % CI [−3.093; 1.256], $I^2 = 95.8$ %; Table 2) indicate a large, but statistically not significant negative effect of RF-EMF exposure, however, the very wide 95 % CI indicates that a large positive effect cannot be ruled out. The heterogeneity of the underlying two studies is considerable (Table 2). Since the results are based on two studies, subgroup analyses were not possible.

3.9.5.1.2. Meta-analysis of accuracy-related outcome measures. Results of the *meta*-analysis for accuracy-related outcome measures (Hedges's g 0.228, 95 % CI [−0.007; 0.463], $I^2 = 0.0$ %; Table 2) indicate a small, but statistically not significant positive effect of RF-EMF exposure on *Motor Skills* (Table 2). Since there was no heterogeneity, there was no need for subgroup analyses.

3.9.5.1.3. Narrative synthesis. Two studies contributed four additional accuracy-related outcome measures, which could not be included in the *meta*-analyses (Besset et al. 2005; Bueno-Lopez et al. 2021) (Table 3). For one of these outcome measures, Hedges's g indicates a small but not statistically significant positive effect, i.e., a higher accuracy under RF-EMF exposure (Bueno-Lopez et al. 2021), which is in line with the results from the corresponding *meta*-analysis.

3.9.5.1.4. Studies not in meta-analyses. There were no studies not providing data for *meta*-analyses.

3.9.6. Domain 6 Concept Formation and Reasoning

3.9.6.1. Concept Formation and Reasoning. The two subclasses *Concept Formation* and *Reasoning* of the cognitive domain *Concept Formation and Reasoning* were investigated in six studies. Two explicitly stated that results for this task – although it was performed – will not be reported (Hamblin et al. 2004; 2006) (Supplementary Data 6). Of the remaining four studies two reported data for speed-related outcome measures only (Keetley et al. 2006; Koivisto et al. 2000b) and two studies (three reports) reported data for both accuracy- and speed-related outcome measures (Haarala et al. 2003b; 2004; 2007).

3.9.6.1.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on this outcome measure (Hedges's g 0.010, 95 % CI [−0.110; 0.129], $I^2 = 0.0$ %; Table 2). Since there was no heterogeneity there was no need for subgroup analyses.

3.9.6.1.2. Meta-analysis of accuracy-related outcome measures. The results of the *meta*-analysis for accuracy-related outcome measures also indicated no significant exposure effect (Hedges's g 0.051, 95 % CI [−0.142; 0.245], $I^2 = 0.0$ %; Table 2). However, the 95 % CI indicates that a small positive effect, i.e., a higher accuracy under RF-EMF exposure, cannot be completely ruled out.

3.9.6.1.3. Narrative synthesis. One study contributed two additional speed-related outcome measures, which could not be included in the *meta*-analyses (Koivisto et al. 2000b) (Table 3). Hedges's g indicated that RF-EMF exposure does not affect speed in *Concept Formation*.

3.9.6.1.4. Studies not in meta-analyses. There were no studies not providing data for *meta*-analyses

3.9.6.2. Concept Formation and Reasoning - Mathematical Procedures. The subclass *Mathematical Procedures* of the cognitive domain *Concept Formation and Reasoning* was investigated in seven studies. One did not report data suitable to be included in the *meta*-analyses (Russo et al. 2006) (Supplementary Data 6). Of the remaining six studies, three (four reports) reported data for speed- and accuracy-related outcome measures (Curcio et al. 2004; Haarala et al. 2003b; 2004; 2007), two reported data for accuracy-related outcome measures only (Eltiti et al. 2009; Hosseini et al. 2019), and one for speed-related outcome measures only (Koivisto et al. 2000b).

3.9.6.2.1. Meta-analysis of speed-related outcome measures. Results of the *meta*-analysis for speed-related outcome measures do not indicate a statistically significant effect of RF-EMF exposure on *Mathematical Procedures* (Hedges's g 0.033, 95 % CI [−0.116; 0.181], $I^2 = 0.0$ %; Table 2). Since there was no heterogeneity there was no need for subgroup analyses.

3.9.6.2.2. Meta-analysis of accuracy-related outcome measures. The results of the *meta*-analysis of accuracy-related outcome measures indicated a small, but statistically not significant positive effect

(Hedges's g 0.232, 95 % CI [−0.121; 0.586], I^2 = 86.1 %; Table 2), i.e., a higher accuracy in *Mathematical Procedures* under RF-EMF exposure. Since heterogeneity of studies was considerable (Figure 13.8 in Supplementary Data 13) subgroup analyses were performed.

The heterogeneity did not considerably change for the subgroups of 1st and 2nd tier studies (Curcio et al. 2004; Eltiti et al. 2009; Haarala et al. 2003b; 2004; 2007), large studies (Eltiti et al. 2009; Haarala et al. 2003b; 2004; 2007; Hosseini et al. 2019), studies on adults without IEI (Curcio et al. 2004; Haarala et al. 2003b; 2004; 2007; Hosseini et al. 2019), studies considering both males and females (Curcio et al. 2004; Eltiti et al. 2009; Haarala et al. 2003b; 2004; Hosseini et al. 2019), studies with head exposure, and studies with governmental or mixed funding (Curcio et al. 2004; Eltiti et al. 2009; Haarala et al. 2003b; 2004; 2007). When only studies with whole body exposure (Eltiti et al. 2009; Hosseini et al. 2019) were considered, heterogeneity dropped to non-important to moderate. Since no parallel-group study and no study on children and/or adolescents were involved, these factors could not be considered for a subgroup analysis (Supplementary Data 12).

3.9.6.2.3. Narrative synthesis. There were no further outcome measures not included in *meta*-analyses.

3.9.6.2.4. Studies not in meta-analyses. One study, which did not contribute data for the *meta*-analyses, concluded that RF-EMF exposure did neither affect speed nor accuracy in a subtraction task (Russo et al. 2006) (Supplementary Data 11, Table 4).

3.10. Publication bias

For all domains / subclasses we assessed, visual inspection of the funnel plot (Supplementary Data 14) suggested no presence of publication bias. For one subclass, (*Working Memory – 1-back Task* speed), we observed a statistically significant Egger's test ($p = 0.071$). However, given the symmetry of the funnel plot, we did not conclude meaningful publication bias.

3.11. Certainty assessment

The results of GRADE assessment for 19 subclasses from five domains are summarized in Table 5 for speed- and accuracy-related outcome measures separately. The assessment is based on the results of the *meta*-analyses only (Table 2), because the results of outcome measures not included in *meta*-analyses and the results of studies not providing numerical values for *meta*-analyses generally did not strongly deviate from the results of *meta*-analyses (see Results of Meta-Analyses).

Domain 1 *Orientation and Attention* is represented by 14 subclasses. For seven of them (*Attentional Capacity, Simple Reaction Time Task*, all 4 difficulty levels of *n-back Task, Mental Tracking*) no downgrading of the certainty of the calculated effect size estimate was necessary for both speed- and accuracy-related outcome measures (if *meta*-analyses could be performed for both kinds of outcome measures). Thus, we conclude with high certainty that RF-EMF exposure results in little to no difference in the outcome.

Four subclasses of Domain 1 were downgraded solely for imprecision, for example, the effect size estimate suggests no difference in the outcome, but the corresponding 95 % CI includes thresholds for an at least small positive (*Concentration / Focused Attention, Vigilance, Processing Speed – Other Tasks*) or negative effect (*>2-Choice Reaction Time Task*), either only for speed-related outcome measures (*Vigilance, Processing Speed – Other Tasks*) or only for accuracy-related outcome measures (*Concentration / Focused Attention, >2-Choice Reaction Time Task*). The certainty of evidence of the respective other outcome measure remained high.

In two subclasses of Domain 1 (*Divided Attention, 2-Choice Reaction Time Task*), the certainty of evidence was high for speed-related outcome measures, but for accuracy-related outcome measures it was low due to inconsistency because of at least moderate heterogeneity as well as imprecision; in one case a small negative effect (*Divided Attention*) and in the other case large effects in either direction (*2-Choice Reaction Time Task*) could not be excluded. In both cases, the effect size estimates for speed-related outcome measures were based on a larger number of studies and participants than the effect size estimates for accuracy-related outcome measures.

For one subclass of Domain 1 (*Selective Attention*) the certainty of evidence was moderate for speed- (because of imprecision) and low for accuracy-related outcome measures (because of imprecision and inconsistency). For both outcome measures, small positive effects of RF-EMF exposure could not be excluded.

In three subclasses of Domain 1 (*Vigilance, Selective Attention, Processing Speed – Other Tasks*), speed-related outcome measures were not downgraded for inconsistency despite at least moderate heterogeneity, because homogenous results were obtained in large subgroups that excluded 3rd tier studies or small-scale studies.

For the vast majority of subclasses of *Orientation and Attention*, we conclude that RF-EMF exposure results in little to no difference in the outcome.

Domain 2 *Perception* is represented by a single subclass (*Visual and Auditory Perception*). The certainty of the calculated effect size estimate was downgraded, because 50 % of the studies that form the body of evidence were 3rd tier studies for both speed- and accuracy-related measures. An additional downgrading of certainty of evidence of speed-related outcome measures occurred due to imprecision (a small negative effect cannot be excluded). We conclude that RF-EMF exposure probably results in little to no difference in accuracy, and may result in little to no difference in speed.

Domain 3 *Memory* is represented by a single subclass (*Verbal and Visual Memory*). The certainty of the calculated effect size estimate was downgraded to moderate for speed-related outcome measures due to imprecision (a small positive effect cannot be excluded), and for accuracy-related outcome measures to low due to inconsistency (at least moderate heterogeneity) and imprecision (large CI covering possible effects in both directions). We conclude that RF-EMF exposure probably results in little to no difference in speed, and may result in little to no difference in accuracy.

Domain 5 *Construction and Motor Performance* is represented by a single subclass *(Motor Skills*). The calculated effect size estimate indicates a small non-significant positive effect for accuracy-related outcome measures, but the certainty of evidence was downgraded to moderate due to imprecision. For the speed-related outcome measures, the calculated effect size estimate indicates a large, statistically non-significant negative effect. Owing to the very wide confidence interval that also includes large positive effects and very high heterogeneity of the results ($I^2 > 90$ %), we downgraded for both inconsistency and imprecision by two levels each. We conclude that RF-EMF exposure may reduce speed, and it probably results in little to no difference in accuracy.

Domain 6 *Concept Formation and Reasoning* is represented by two subclasses. For both, no downgrading of the certainty of evidence was necessary for speed-related outcome measures. The two accuracy-related outcome measures had to be downgraded to moderate for *Reasoning* due to imprecision (a small positive effect cannot be excluded), and to low for *Mathematical Procedures* due to both imprecision (Hedges's g indicates a small positive effect, but the absence of an effect cannot be excluded) and inconsistency (heterogeneity at least moderate). Thus, we conclude that RF-EMF exposure results in little to no difference in speed, and it may result in little to no difference in accuracy.

No domain / subclass was downgraded because of indirectness or publication bias.

It is important to note that we downgraded the quality of evidence if negative or positive effects cannot be ruled out. However, the results indicate that for 26 of the 35 of either speed- or accuracy-related outcome measures of particular subclasses, the certainty of no adverse effects is high (see "remarks" columns in Table 5).

Table 5
Grading of Recommendations Assessment, Development, and Evaluation (GRADE) based on study limitations (50% 3rd tier studies), imprecision (95% confidence interval [CI]), inconsistency (I^2 cutoff of 30%), and indirectness (study population), for speed- and accuracy-related outcome measures of cognitive domains and subclasses, respectively.

			Certainty assessment							Summary of findings					
										No of participants		Effect size			
Domain	Subclass	Outcome measure	No of studies	Design (Cross-over / Parallel-groups)	Distribution of study quality	Study limitations	Inconsistency	Indirectness	Imprecision	Exposure	Comparator	Hedges's g	95% CI	Certainty	Remarks
D1	Attention – Attentional Capacity	Accuracy	5	3/2	1st tier: 1 2nd tier: 3 3rd tier: 1	0	0	0	0	435	436	0.024	[−0.101; 0.149]	⊗⊗⊗⊗	high certainty for no effect
D1	Attention – Concentration / Focused Attention	Speed	3	3/0	1st tier: 1 2nd tier: 2 3rd tier: 0	0	0	0	0	132	132	0.005	[−0.171; 0.180]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	4	3/1	1st tier: 1 2nd tier: 3 3rd tier: 0	0	0	0	−1 a)	189	190	0.097	[−0.049; 0.244]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
D1	Attention – Vigilance	Speed	7	7/0	1st tier: 4 2nd tier: 2 3rd tier: 1	0	0 h)	0	−1 a)	247	247	0.118	[−0.044; 0.279]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
		Accuracy	6	6/0	1st tier: 4 2nd tier: 2 3rd tier: 0	0	0	0	0	199	199	0.042	[−0.094; 0.178]	⊗⊗⊗⊗	high certainty for no effect
D1	Attention – Selective Attention	Speed	13	13/0	1st tier: 4 2nd tier: 8 3rd tier: 1	0	0 h)	0	−1 a)	452	452	0.080	[−0.089; 0.250]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
		Accuracy	10	8/2	1st tier: 2 2nd tier: 6 3rd tier: 2	0	−1 e)	0	−1 a)	432	433	0.178	[−0.022; 0.378]	⊗⊗OO	low certainty for no effect / moderate certainty for no negative effect
D1	Attention – Divided Attention	Speed	6	5/1	1st tier: 2 2nd tier: 3 3rd tier: 1	0	0	0	0	261	266	−0.010	[−0.142; 0.122]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	4	3/1	1st tier: 2 2nd tier: 1 3rd tier: 1	0	−1 e)	0	−1b)	131	136	−0.089	[−0.354; 0.176]	⊗⊗OO	low certainty for no effect
D1	Processing Speed – Simple Reaction Time Task	Speed	14	13/1	1st tier: 5 2nd tier: 5 3rd tier: 4	0	0	0	0	792	793	0.069	[−0.020; 0.159]	⊗⊗⊗⊗	high certainty for no effect
D1	Processing Speed – 2-Choice Reaction Time Task	Speed	9	8/1	1st tier: 5 2nd tier: 3 3rd tier: 1	0	0	0	0	373	374	−0.023	[−0.125; 0.079]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	3	3/0	1st tier: 3 2nd tier: 0 3rd tier: 0	0	−1 e)	0	−1c)	117	117	−0.063	[−0.376; 0.250]	⊗⊗OO	low certainty for no effect

(*continued on next page*)

Table 5 (*continued*)

			Certainty assessment							Summary of findings					
										No of participants		Effect size			
Domain	Subclass	Outcome measure	No of studies	Design (Cross-over / Parallel-groups)	Distribution of study quality	Study limitations	Inconsistency	Indirectness	Imprecision	Exposure	Comparator	Hedges's g	95% CI	Certainty	Remarks
D1	Processing Speed – >2-Choice Reaction Time Task	Speed	7	6/1	1st tier: 2 2nd tier: 3 3rd tier: 2	0	0	0	0	516	517	−0.054	[−0.140; 0.033]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	3	3/0	1st tier: 2 2nd tier: 1 3rd tier: 0	0	0	0	−1b)	131	131	−0.129	[−0.298; 0.041]	⊗⊗⊗O	moderate certainty for no effect
D1	Processing Speed – Other Tasks	Speed	6	5/1	1st tier: 1 2nd tier: 5 3rd tier: 0	0	0 i)	0	−1 a)	239	239	0.067	[−0.121; 0.256]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
		Accuracy	5	4/1	1st tier: 2 2nd tier: 2 3rd tier: 1	0	0	0	0	304	304	0.036	[−0.080; 0.152]	⊗⊗⊗⊗	high certainty for no effect
D1	Working Memory – 0-back Task	Speed	8	8/0	1st tier: 4 2nd tier: 2 3rd tier: 2	0	0	0	0	267	267	−0.032	[−0.149; 0.086]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	8	8/0	1st tier: 4 2nd tier: 2 3rd tier: 2	0	0	0	0	267	267	0.060	[−0.057; 0.178]	⊗⊗⊗⊗	
D1	Working Memory – 1-back Task	Speed	11	11/0	1st tier: 6 2nd tier: 3 3rd tier: 2	0	0	0	0	420	420	−0.090	[−0.184; 0.004]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	9	9/0	1st tier: 5 2nd tier: 2 3rd tier: 2	0	0	0	0	283	283	0.005	[−0.109; 0.119]	⊗⊗⊗⊗	
D1	Working Memory – 2-back Task	Speed	13	13/0	1st tier: 8 2nd tier: 3 3rd tier: 2	0	0	0	0	474	474	−0.044	[−0.132; 0.044]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	10	10/0	1st tier: 6 2nd tier: 2 3rd tier: 2	0	0	0	0	313	313	−0.054	[−0.163; 0.054]	⊗⊗⊗⊗	
D1	Working Memory – 3-back Task	Speed	10	10/0	1st tier: 6 2nd tier: 3 3rd tier: 1	0	0	0	0	398	398	−0.018	[−0.114; 0.079]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	7	7/0	1st tier: 4 2nd tier: 2 3rd tier: 1	0	0	0	0	237	237	0.027	[−0.097; 0.152]	⊗⊗⊗⊗	
D1	Working Memory – Mental Tracking	Accuracy	7	5/2	1st tier: 2 2nd tier: 3 3rd tier: 2	0	0	0	0	400	401	−0.047	[−0.146; 0.052]	⊗⊗⊗⊗	high certainty for no effect
D2	Perception – Visual and Auditory Perception	Speed	2	2/0	1st tier: 1 2nd tier: 0 3rd tier: 1	−1f)	0	0	−1b)	84	84	−0.015	[−0.225; 0.195]	⊗⊗OO	low certainty for no effect
		Accuracy	4	4/0	1st tier: 1 2nd tier: 1 3rd tier: 2	−1f)	0	0	0	137	137	0.035	[−0.129; 0.199]	⊗⊗⊗O	moderate certainty for no effect

(*continued on next page*)

Table 5 (*continued*)

			Certainty assessment							Summary of findings					
										No of participants		Effect size			
Domain	**Subclass**	**Outcome measure**	**No of studies**	**Design (Cross-over / Parallel-groups)**	**Distribution of study quality**	**Study limitations**	**Inconsistency**	**Indirectness**	**Imprecision**	**Exposure**	**Comparator**	**Hedges's g**	**95% CI**	**Certainty**	**Remarks**
D3	Memory – Verbal and Visual Memory	Speed	3	3/0	1st tier: 1 2nd tier: 1 3rd tier: 1	0	0	0	−1 a)	102	102	0.042	[−0.148; 0.231]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
		Accuracy	10	7/3	1st tier: 1 2nd tier: 6 3rd tier: 3	0	−1 e)	0	−1c)	525	526	−0.087	[−0.376; 0.203]	⊗⊗OO	low certainty for no effect
D5	Construction and Motor Performance – Motor Skills	Speed	2	2/0	1st tier: 1 2nd tier: 1 3rd tier: 0	0	−2 e) g)	0	−2c), d)	42	42	−0.919	[−3.093; 1.256]	OOOO	very low certainty for a large negative effect
		Accuracy	3	3/0	1st tier: 1 2nd tier: 2 3rd tier: 0	0	0	0	−1 d)	81	82	0.228	[−0.007; 0.463]	⊗⊗⊗O	moderate certainty for a small positive effect / high certainty for no negative effect
D6	Concept Formation and Reasoning – Reasoning	Speed	4	4/0	1st tier: 1 2nd tier: 2 3rd tier: 1	0	0	0	0	263	263	0.010	[−0.110; 0.129]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	2	2/0	1st tier: 1 2nd tier: 1 3rd tier: 0	0	0	0	−1 a)	100	100	0.051	[−0.142; 0.245]	⊗⊗⊗O	moderate certainty for no effect / high certainty for no negative effect
D6	Concept Formation and Reasoning – Mathematical Procedures	Speed	4	4/0	1st tier: 1 2nd tier: 2 3rd tier: 1	0	0	0	0	168	168	0.033	[−0.116; 0.181]	⊗⊗⊗⊗	high certainty for no effect
		Accuracy	5	5/0	1st tier: 2 2nd tier: 2 3rd tier: 1	0	−1 e)	0	−1 d)	253	253	0.232	[−0.121; 0.586]	⊗⊗OO	low certainty for a small positive effect / moderate certainty for no negative effect

a) there is a low probability for a positive effect because the 95% CI includes + 0.2.
b) there is a low probability for a negative effect because the 95% CI includes −0.2.
c) Extremely low confidence in the calculated effect size: The 95% CI is very wide and includes large effects in both directions.
d) Hedges's g indicates an effect, but the 95% CI includes zero.
e) moderate or substantial heterogenity.
f) the number of 3rd tier studies is ≥ 50%.
g) $I^2 \geq 90\%$.
h) no downgrading for heterogeneity (large subgroup of 1st tier and 2nd tier studies: $I^2 = 0\%$).
i) no downgrading for heterogeneity (large subgroup of studies with sample size >30: $I^2 = 0\%$).
Abbreviations: CI – Confidence Interval, D1 – D6 – Domain 1 – Domain 6, EMF – electromagnetic field, No – number.

3.12. Summary of the results

As outlined in the preceding sections, no statistically significant effect of RF-EMF exposure on performance was observed in the *meta*-analyses for any of the investigated domains and subclasses of cognitive function as assessed by speed- and accuracy-related outcome measures (Table 2). In 20 out of 35 *meta*-analyses, the value of the effect size estimate (Hedges's g) as well as the corresponding 95 % confidence interval (CI) indicate that RF-EMF exposure results in little to no difference in the outcome, and that the certainty of evidence of most of these results is high (Table 2, Table 5).

4. Discussion

4.1. Interpretation of the results

Overall, the results from all domains and subclasses across their speed- and accuracy-related outcome measures provide consistent evidence that short-term RF-EMF exposure is not associated with a negative effect on cognitive performance in human experimental studies, although for some domains / subclasses (16 out of 35) some uncertainty remains, mainly because of limitations in the study quality, inconsistency in the results, or imprecision of the combined effect size estimate. For speed-related outcome measures some uncertainty in the evidence for no difference in outcome applies to D1 *Vigilance, Selective Attention, Processing Speed – Other Tasks*, D2 *Perception*, D3 *Memory*, and D5 *Construction and Motor Performance*, whereas for accuracy-related outcome measures this applies to D1 *Concentration / Focused Attention, Selective Attention, Divided Attention, 2-Choice Reaction Time, >2-Choice Reaction Time*, D2 *Perception*, D3 *Memory*, D5 *Construction and Motor Performance*, and D6 *Concept Formation and Reasoning, Mathematical Procedures*. However, in most of these cases (11 out of 16), this relates to bodies of evidence for which.

- the certainty of evidence for no effect is moderate (one out of 16), or
- the certainty of evidence for no negative effect is high (seven out of 16), or
- the certainty of evidence for no negative effect is moderate (three out of 16).

For three of the remaining five domains / subclasses, the certainty of evidence for no effect is low for one outcome measure, but for the same subclass there is a high (two out of five) to moderate (one out of five) certainty of evidence for no effect in the other respective outcome measure (speed or accuracy), for which a larger sample size is available (D1 *Divided Attention, 2-Choice Reaction Time*, D2 *Perception*). This increases confidence that all these subclasses of cognitive function domains are not negatively affected by RF-EMF exposure.

There remain two subclasses of cognitive performance domains for which a less robust assessment is possible based on the GRADE assessment only.

4.1.1. Memory

For D3 *Memory*, the accuracy-related outcome measure has the larger sample size (>500 participants), and exhibits a result with substantial heterogeneity ($I^2 = 85.2$ %) and an effect size estimate, for which a small negative or positive effect cannot be ruled out (Hedges's g = −0.087, 95 % CI = [−0.376; 0.203]). Thus, for accuracy of D3 *Memory*, there is a low certainty of evidence for lack of a negative effect. The predefined subgroup analyses did not provide an explanation for the observed heterogeneity, but there is one study in the body of evidence (Krause et al. 2004) that differs strongly from the other results, because it reports an extremely large negative effect (Hedges's g = −3,281, 95 % CI = [−4.287, −2.276]). This finding was in contrast to the result of an earlier study by the same research group (Krause et al. 2000a), in which performance on the same task was not affected by RF-EMF. The error rate in this earlier study was similar to that reported in the sham condition of the replication study (Krause et al. 2004). The authors themselves stated that the "…*result remains an unreplicated and unexplained response*" (Krause et al. 2004, p. 39). Since half of the subjects (n = 12 subjects) started with EMF exposure while performing the task for 30 min and then switched to the sham condition, while still performing the task for another 30 min, the other half started off with the sham exposure condition, followed by RF-EMF exposure. A total test duration of 60 min might have affected the subgroups differently regarding their attention capacity. Furthermore, it remains unclear whether the daytime of testing was kept constant in all participants. Temporal circadian changes in attention can therefore not be ruled out and might have been a possible confounding factor.

4.1.2. Construction and Motor performance

The speed category of D5 *Construction and Motor Performance* is the only domain that indicates a large negative effect, however, with very low certainty of evidence. The result with substantial heterogeneity (I^2 = 95.8 %) is obtained from only two double-blind cross-over studies (Curcio et al. 2008; Lustenberger et al. 2013) with a low number of adult participants (24 and 18, respectively). While the effect size of one study indicates no effect (Curcio et al. 2008, Hedges's g = 0.162, 95 % CI [−0.228; 0.552]), the other points to a large negative effect (Lustenberger et al. 2013, Hedges's g: −2.068, 95 % CI [−2.862; −1.253]). No predefined subgroup analysis was possible for this body of evidence, but it is noted that the experimental procedures and speed-related outcome measures for the applied sequential finger tapping task (SFFT) were quite different. While Curcio et al. (2008) looked at immediate effects of RF-EMF on tapping time, i.e., the time to complete the task, Lustenberger et al. (2013) investigated overnight performance changes of the variance of reaction time in subjects being exposed during the whole sleep episode. Lustenberger et al. (2013) did not report data on mean reaction time, tapping time or accuracy-related outcome measures, making comparisons with other studies impossible. It is important to note that the accuracy measure of D5 *Construction and Motor Performance* includes more studies (n = 3 studies) and participants (n = 109 participants) than the speed measure (n = 2 studies, n = 42 participants), and provides even moderate evidence for a small positive effect, while the certainty of no negative effect is high.

4.2. Comparison with former findings

To date, four *meta*-analyses on the effects of RF-EMF exposure on cognitive performance have been conducted (Barth et al. 2008; 2012; Valentini et al. 2010; Zubko et al. 2017). The most recent search, which was restricted to the cognitive domain of working memory (Zubko et al. 2017), ended in August 2013. Twelve of the 50 studies included in the present *meta*-analyses, were published after this date. Furthermore, the number of studies included in the *meta*-analyses varies from 10 to 24. Only five studies were included in all four *meta*-analyses. In the previous publications, *meta*-analyses were performed for specific tasks, with the exception of Zubko et al. (2017), who focused on working memory (domain *Orientation and Attention* according to Lezak et al. (2012), see Outcomes); the other three publications included tasks belonging to the domains Orientation and Attention or *Concept Formation and Reasoning*. No other cognitive domain was addressed in the four systematic reviews with *meta*-analyses. The four studies differ with regard to quality assessment of the included studies. While Barth et al. (2008; 2012) did not perform a quality assessment, Valentini et al. (2010) used a three-stage quality assessment, and Zubko et al. (2017) finally used the RoB tool developed by OHAT. None of the four *meta*-analyses evaluated the certainty of the evidence of their results according to GRADE.

The *meta*-analysis published by Barth et al. (2012) considers 17 different studies on human cognitive performance, all of which were also included in our present review and *meta*-analyses. The studies represented tasks from Domain 1 *Orientation and Attention* and from

Domain 6 *Concept Formation and Reasoning*. RF-EMF exposure from GSM and UMTS mobile phones did not have a statistically significant effect on performance in the *meta*-analysis of Barth et al. (2012). The authors concluded that a significant short-term effect of RF-EMF exposure can in principle be excluded. The result of their *meta*-analysis is consistent with the present finding of no effect in the respective domains.

In their *meta*-analysis on possible effects of EMF emitted by GSM phones on working memory in n-back tasks, subtraction tasks, and digit span tasks, Zubko et al. (2017) did not find any effect of RF-EMF exposure on speed- and accuracy-related outcome measures of the respective cognitive tests of ten studies, nine of which were also included in our *meta*-analyses. The results are consistent with the findings of our *meta*-analysis on the subclasses of D1 *Attentional Capacity and Working Memory* (digit span tasks, n-back tasks) and D6 *Mathematical Procedures* (subtraction task).

In conclusion, our results are consistent with previous *meta*-analyses and reviews that found no or only small and no harmful effects of RF-EMF on cognitive performance.

4.3. Limitations in the evidence for RF-EMF effects on cognitive performance outcomes

A number of limitations need to be considered when interpreting the results of the review.

4.3.1. Frequency range

In this systematic review we aimed to collect and assess the available evidence in the frequency range 100 kHz – 300 GHz. As outlined in Supplementary Data 7 and Supplementary Data 8, the included studies only provide data for a very narrow frequency range of 400 MHz – 2450 MHz, with the vast majority (64 %) of studies conducted at 900 MHz. The reason why 900 MHz has been studied so often is because it is historically the longest used frequency band in digital cellular mobile communication technology. At first glance, it appears difficult to draw generalized conclusions for the whole range of RF-EMF from this evidence base. However, for the physical agent RF-EMF with frequencies above 10 MHz, there is no biophysically plausible mechanism, other than depositing RF energy, and the frequencies studied still penetrate deep enough to expose brain tissue. The higher the RF-EMF frequencies, the exposure levels in the brain decrease due to reduced penetration depth which renders a potential interaction with cognitive functions less likely for frequencies above a few GHz.

Other properties of the exposure also might be important for eliciting a biological reaction which might be relevant to the outcomes investigated here. Most of the included studies used GSM-like modulations, a modulation scheme that comprises low frequency components in the envelope of the modulated signal. This type of signal is considered to have the highest potential to elicit biological reactions in the brain and yet there is no robust evidence of an effect on cognitive function. We therefore are very confident that the result of this SR can be interpolated to other frequencies and modulation schemes. The only exception is the RF-EMF frequency range from 100 kHz to 10 MHz. Here, other mechanisms, such as direct stimulation of nerve cells by the induced electric field, or an effect of the radical pair mechanism on biochemical reactions involving radicals, are biophysical mechanisms that have to be considered as potential modes of action. We did not identify any eligible study in this frequency range, which is a major limitation of the available evidence.

4.3.2. Risk of bias in studies

Exposure generation and assessment: In the majority of the studies, very controlled exposure signals were applied, but only in about 20 to 30 % of the studies (Fig. 3, definitely or probably low risk of bias in exposure generation and assessment) the exposure information was detailed enough for enabling potential dose–response analyses. This is because the absorption distribution of RF-EMF energy in the brain is highly localized and strongly dependent on antenna characteristics, location, distance, and orientation with respect to the body. Therefore, numerical simulations on heterogeneous body models that adequately represent the experimental conditions, are needed to reliably map the spatial distribution of SAR in the brain. It is not known, whether a special brain region needs to be particularly exposed to a certain level in order to alter cognitive performance (if possible at all). Given the variety of investigated exposure situations (and consequently different spatial distributions of SAR-levels in the brain), it cannot be ruled out that a certain proportion of the studies were not suitable to elicit a response, which would then bias the overall effect size estimate towards no effect, although for every included study the exposure contrast in (at least a part of) the brain was sufficient.

Selective reporting: Many studies reported data for several domains / subclasses and furthermore used multiple tests to address effects within these domains / subclasses. In several studies, the performed tests could have, in principle, provided results for speed- and accuracy-related measures separately; however, in several instances this was not the case, and only speed or accuracy measures were investigated. We considered selective reporting bias in RoB assessment if the method section of a study stated that a particular outcome was measured, but it was not reported in the results section (RoB Question 10). This leaves a small risk of reporting bias in additional studies, which did not mention outcomes in the methods section if they were not reported in the results.

4.3.3. Other limitations

Statistical power: Very few (8 %) of the single studies included in the *meta*-analyses considered sample size prior to design the study, and only few studies addressed power in the discussion of their results. Finally, the number of studies, on which results for speed- and accuracy-related outcomes were available for *meta*-analyses, varied considerably from two to 14 with 42 to 820 subjects.

Heterogeneity in studies and results: The reported results varied to some extent, resulting in an at least moderate heterogeneity in nine out of 35 *meta*-analyses. Using subgroup analyses (Supplementary Data 12), we tried to identify possible sources of heterogeneity, and this approach was successful in three out of four speed-related outcome measures with at least moderate heterogeneity.

For the five accuracy-related outcome measures with at least moderate heterogeneity, we could not identify possible sources of heterogeneity in the subgroup analyses. However, for those domains / subclasses, for which at least five studies contribute to the *meta*-analysis result, it appears that heterogeneity is at least partly driven by one outlier study contributing values that strongly differ from the other results in terms of mean value and 95 % CI, Supplementary Data 13):

- D1 *Selective Attention*: The 2nd tier study Besset et al. (2005) contributes the only large statistically significant positive effect (Hedges's g: 1.49, 95 % CI = [0.899, 2.081]; Figure 13.3 in Supplementary Data 13). Exclusion of this study from the *meta*-analysis would lead to a very homogeneous result ($I^2 = 0$ %), indicating a statistically significant positive effect, albeit with an effect size below the threshold for a small effect (Hedges's g: 0.104, 95 % CI [0.009, 0.200]).
- D3 *Memory*: The 2nd tier study Krause et al. (2004) contributes the only large statistically significant negative effect (Hedges's g: −3.281, 95 % CI = [−4.287, −2.276]; Figure 13.7 in Supplementary Data 13). The heterogeneity of the results decreases from $I^2 = 85.2$ % to $I^2 = 52.6$ % when this study is excluded from the *meta*-analysis, suggesting that the study is only partially responsible for the observed heterogeneity. Without this study, the estimate of the overall effect size shifts slightly to positive values with a much narrower confidence interval (Hedges's g: 0.092, 95 % CI [−0.074, 0.257].)
- D6 *Mathematical Procedures*: The 1st tier study Haarala et al. (2003b) contributes the only large statistically significant positive effect

(Hedges's g: 0.892, 95 % CI = [0.605, 1.179]; Figure 13.8 in Supplementary Data 13). A closer look at the published data (Haarala et al. 2003b, Table 2 in their publication) reveals that there is a single strikingly high value (approximately 10-times higher than all other presented values of the same parameter) in the subtraction task in one of the two conditions (EMF OFF) in a subsample (Swedish participants). Since all other values are similar in the Swedish and Finnish participants in the EMF ON condition, this value might most probably be due to a typo or an outlier due to other reasons not mentioned by the authors. Exclusion of Haarala et al. (2003b) from *meta*-analysis would lead to a quite homogenous result ($I^2 = 24.1$ %) that indicates no statistically significant effect, although a small positive effect can still not be ruled out (Hedges's g: 0.078, 95 % CI [−0.090; 0.246]).

In general, the speed measure itself, which was operationalized in most of the tasks by reaction time, is a rather homogeneous measure compared to the wide range of different accuracy measures, which were grouped and considered together according to the main cognitive domain of the respective tests. Accuracy measures vary widely in terms of their respective outcome parameters (e.g., errors, correct reactions, omissions, or even more complex composite scores) and the units reported (e.g., numbers, percentages, difference scores).

Since RF-EMF-induced effects, if they exist, are expected to be small, and since human experimental studies usually allow only a limited number of subjects to be investigated, factors that might affect the outcome measure and thus increase the variability of the results, should be controlled for as much as possible. In this respect the studies included in our *meta*-analyses differed, among others, with regard to the following factors:

- The presence of a separate *practice session*, which has been reported to be performed in about two thirds of the studies, at least for some of the tests. In studies, where no practice session was performed, a learning effect may outweigh the possible effect of exposure.
- The *task order*, which is important with regard to changes in the level of vigilance/attention in longer sessions, where more than one test is applied. Some studies did not report the order, some studies used a counterbalanced order, while others used a fixed order.
- The *timing of test sessions*. In 20 % of the studies, test sessions for different exposures were performed on the same day, which entails a high risk of bias by carry-over effects (Risk of Bias question 6).
- The *duration of the test session*, which was not reported in 30 % of the studies. In the remaining studies it varied from 30 min to more than five hours.
- The control of *mobile phone use* prior to the test session, which is not reported in 58 % of the studies.
- The control of *handedness*. Thirteen studies did not report handedness, 32 reported to have included only right-handed subjects, and five included both right- and left-handed subjects. For a discussion of a relationship between handedness and cognitive performance see Lezak et al. (2012).
- The *time of assessment of outcome measures*. In approximately half of the studies, cognitive performance was assessed during exposure, in 6 % assessments were only made after exposure, and in other studies assessment was made at different combinations of times (before and after; before and during; during and after; before, during and after exposure).
- The *cognitive tests* used to assess a specific cognitive domain / subclass and the variability in details of cognitive test assessments / performance.
- *Exposure conditions* applied, for example, frequency, modulation, duration, and spatial distribution.

It is unlikely that the results of the present *meta*-analyses would have been quite different, i.e., that an effect would have been observed if the factors mentioned above had been taken into account. Nevertheless, future studies should control for all these factors and follow the guidelines for research in this area already published by Regel and Achermann (2011).

4.4. Limitations in the review process

Missing data: Out of the 76 studies, on which the systematic review is based, we had to contact the authors of 40 studies for additional information in order to calculate effect sizes (see Supplementary Data 9). Seven authors representing nine studies did not answer. Additionally, one mail could not be delivered. For 24 studies, the requested information could not be provided. However, for eight of these publications, information on means and dispersion (SEM or SD, respectively) was extracted with WebPlotDigitizer software (https://automeris.io/WebPlotDigitizer/), which is the most precise way possible albeit not errorless. Although not all information was available for *meta*-analysis in this systematic review, there is evidence that the sample of studies that were included in *meta*-analysis is representative with respect to most properties: Supplementary Data 8 shows that the sample of studies with data does not statistically significantly differ from those studies, which could not contribute data with regard to the conflict of interest statements (COI), study design, blinding, population, sex distribution, region of exposure, exposure system, frequency of exposure, modulation, risk of bias, number of investigated domains per study, number of studies investigating the domains D1 to D7. However, statistically significant differences in the distribution between the samples of studies were observed for the funding source (fewer studies with not reported information in the *meta*-analysis sample) and the SAR levels (fewer studies with not reported SAR levels in the *meta*-analysis sample, see Supplementary Data 8 for details).

Aggregation procedure: For some studies an aggregation procedure (see Data extraction and aggregation for the *meta*-analyses) was performed to avoid unit of analysis issues that come along when shared controls were used in the studies, and to get comparable information across studies, respectively. It can thus not be ruled out that responses that are only associated with a specific characteristic of the exposure / location / population etc., have been averaged out by the aggregation, which would then be a bias towards no effect.

Cross-over studies in meta-analyses: A general source of uncertainty is the correlation between repeated measurements in cross-over studies. In the present analyses, this correlation is set to 0.5 across all calculations (Supplementary Data 5, Fu et al. (2008)). In cases where the actual underlying correlation is larger than 0.5, this leads to an overestimation of the width of the 95 % CI; in cases where the actual correlation is lower than 0.5, this leads to an underestimation of the width of the 95 % CI. However, it is highly unlikely that the impact will be such as to change the conclusions of this review.

Multiple outcomes: Many studies reported multiple outcomes (see Supplementary Data 6) per domain / subclass. If possible, we have chosen to include those outcome measures into *meta*-analyses, which have been used in the majority of the other studies as well, or those that best addressed the specific domain / subclass according to Lezak et al. (2012). It would also have been possible to calculate effect sizes for all outcomes and select the worst case for *meta*-analyses. Data not included in *meta*-analyses were described narratively (Table 3). Mostly they are consistent with the results of *meta*-analyses.

Although the applied procedure appeared to be successful in providing homogenous results in many *meta*-analyses, this is not true for all of them. The combination of quite different tasks within a cognitive domain / subclass might have led to the observed substantial heterogeneity in accuracy measures in three subclasses of D1 *Orientation and Attention*, in D3 *Memory* and in D6 *Mathematical Procedures*, which could not be explained by predefined subgroup analyses. This hypothesis is supported by the, in contrast, high homogeneity of different studies applying more similar tests within a domain / subclass, such as the n-back tasks and simple reaction time tasks. A limitation of the present systematic review might therefore be the combination of quite different tasks within one cognitive domain or subclass. On the other hand, further differentiation between tasks and outcome measures would have led to even more subclasses of tasks, which most often belong to the same research group, introducing another possible bias, and counteracting against the comprehensive approach of a systematic review. Nevertheless, considering speed as the only performance outcome measure would have resulted in less heterogeneity and has been considered as the only primary outcome parameter in previous systematic reviews and *meta*-analyses on human cognitive function (e.g., Valentini et al. 2011).

4.5. Implications of practice and policy

The present systematic review provides mostly moderate to high certainty of evidence that short-term RF-EMF exposure at SAR levels within the recommended limits (ICNIRP 2010) does not negatively affect the investigated domains of cognitive function.

4.6. Implications for research

Although the number of studies and participants is low for several domains / subclasses, the certainty of evidence for lack of an effect is very low only for the speed category of D5 *Construction and Motor Performance*. Only two small studies with a total number of 42 participants contribute to the result with substantial heterogeneity and the body of evidence suggests a large negative effect with very low certainty. Further studies are needed to confirm or refute this effect. In particular, all outcome measures used in both studies should be considered and reported numerically.

The number of studies that provide age-specific information on RF-EMF effects on cognitive performance is small. In particular, only five of the included studies were performed in children and only one in the elderly. Since children are generally considered to be a sensitive group, and the cognitive performance tends to decline with age, studies in children/adolescents and in elderly subjects are recommended to investigate whether these both age groups are more affected by RF-EMF exposure than young adults. Since the subgroup analyses (Supplementary Data 12) provide weak indications for a possible effect of sex, analyses stratified for sex of the participants are recommended.

In general, any new study should be designed in a way that any potential RoB is minimized. The criteria for definitely low RoB are summarized in Supplementary Data 8 of the protocol (Pophof et al. 2021). Furthermore, power calculations should be conducted prior to the final study design and study power should be sufficient for detecting even small effects. A comprehensive list of further issues that should be considered when conducting studies on possible effects of RF-EMF on cognitive performance, are published in Regel and Achermann (2011).

Authors of future studies are encouraged to make the original individual data publicly available in appropriate data repositories to avoid missing data due to incomplete reporting.

5. Other information

5.1. Registration and protocol

The protocol for this review was registered in Prospero, reg. no. CRD42021236168 and published in Environment International (Pophof et al. 2021).

5.2. Deviations from the protocol

In the protocol, we did not describe how the ratings of the individual RoB questions for a given study would be used to define an overall quality rating for that study. This admission could be considered as a potential risk of bias for this systematic review if, for example, certain studies were selectively included/excluded from subgroup analyses based on the quality rating. However, given that the heterogeneity of effects across studies was low for most outcome measures, such selective analysis would in principle have little to no impact. The GRADE assessment, however, strongly depends on the overall study quality assessment. Thus, in order to be as transparent as possible, we have explained and justified the chosen method for allocating studies to quality tiers in detail in Methods – Risk of Bias assessment.

We did not conduct separate analyses for individuals with and without IEI-EMF, because there were only seven studies including subjects with IEI. Only six of the seven studies provided numerical data (for only some domains / subclasses) to be used to calculate effect sizes. The data of these six studies do not allow a detailed analysis following the approach pursued in this paper.

Because there was only one study investigating females, heterogeneity could not be assessed for this subgroup. Therefore, we performed subgroup analyses stratified by studies investigating only males, and studies investigating males and females together. However, the explanatory power of this approach should not be overestimated.

We did not evaluate a potential dose–response relationship or perform subgroup analyses regarding exposure levels, because independently from the exposure level there was predominantly no effect of RF-EMF, and the exposure assessment in most studies did not provide spatially resolved exposure levels in the brain. For similar reasons we did not analyse the exposure category D separately from A, B and C (see Protocol, Pophof et al. 2021), but combined all exposure categories in analyses.

Due to the huge amount of data available for the domains D1 and to a lesser extent for D6, and due to the fact that some studies reported results for a large number of different subclasses of domains, a problem with the unit of analysis would have resulted in a huge amount of original data that could not be used for a *meta*-analysis if we had kept the outcome categories defined in the protocol. Therefore, we defined more detailed outcome categories according to the domain subclasses (Table 1) as defined by Lezak et al. (2012, Part II The Compendium of Tests and Assessment Techniques, p. 391 ff.). This enables a better differentiation of different cognitive abilities, and increases the number of possible *meta*-analyses and a higher proportion of original data included in the *meta*-analyses.

In order to explore possible sources of heterogeneity, we additionally included a stratification according to sample sizes (<30; ≥ 30). Studies with small sample sizes are likely to have a higher variability than studies with larger sample sizes.

Deviating from the protocol, we did not conduct subgroup analyses for the exposure-related categories of

- signals with different modulation,
- time course of exposure,
- near-field vs far-field exposure sources,
- different frequencies,

for the nine outcome measures of subclasses with results with at least moderate heterogeneity (Table 2). This is because a large number of studies falls in the category "continuous GSM-modulated near-field exposure with frequency lower than 1 GHz" (in six out of these nine outcome measures at least half of results include this exposure category) and most of the outlier studies that strongly contribute to heterogeneity of the results also fall into this category (five studies).

CRediT authorship contribution statement

Blanka Pophof: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Jens Kuhne:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Gernot Schmid:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Evelyn Weiser:** Writing – review & editing, Visualization, Validation, Methodology, Data curation. **Hans Dorn:** Writing – review & editing, Validation, Methodology, Data curation. **Bernd Henschenmacher:** Validation, Project administration, Data curation. **Jacob Burns:** Writing – review & editing, Methodology. **Heidi Danker-Hopfe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Cornelia Sauter:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. BP is member of the ICNIRP Scientific Expert Group (SEG) on environment, BfS observer in the working group SSK-A630 of the German Commission on Radiological Protection and was German delegate of European Cost Actions BM0704 and BM1309 "EMF-MED". GS is member of the Committee "Non-Ionizing Radiation" (SSK-A6) and member of the working group SSK-A630 of the German Commission on Radiological Protection. GS is chair of the Austrian Standardization Sub-Committee TSK-EMV-EMF "Electromagnetic Fields". HDHs research is entirely funded by public or not-for-profit foundations. She has served as advisor to a number of national and international public advisory groups concerning the potential health effects of exposure to non-ionizing radiation, including the World Health Organization, the German Commission on Radiological Protection (member of the committee "Non-Ionizing Radiation" (SSK-A6) and member of the working group 5G (SSK-A630)) and the Independent Expert Group of the Swedish Radiation Safety Authority. JK is member of the ICNIRP Scientific Expert Group (SEG) on ultrasound and BfS observer in the working group SSK-A630 of the German Commission on Radiological Protection.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108899.

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