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The association between real-life markers of phone use and cognitive performance, health-related quality of life and sleep

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A R T I C L E I N F O

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A B S T R A C T

Introduction: The real-life short-term implications of electromagnetic fields (RF-EMF) on cognitive performance and health-related quality of life have not been well studied. The SPUTNIC study (Study Panel on Upcoming Technologies to study Non-Ionizing radiation and Cognition) aimed to investigate possible correlations between mobile phone radiation and human health, including cognition, health-related quality of life and sleep.
Methods: Adult participants tracked various daily markers of RF-EMF exposures (cordless calls, mobile calls, and mobile screen time 4 h prior to each assessment) as well as three health outcomes over ten study days: 1) cognitive performance, 2) health-related quality of life (HRQoL), and 3) sleep duration and quality. Cognitive performance was measured through six "game-like" tests, assessing verbal and visuo-spatial performance repeatedly. HRQoL was assessed as fatigue, mood and stress on a Likert-scale (1–10). Sleep duration and efficiency was measured using activity trackers. We fitted mixed models with random intercepts per participant on cognitive, HRQoL and sleep scores. Possible time-varying confounders were assessed at daily intervals by questionnaire and used for model adjustment.
Results: A total of 121 participants ultimately took part in the SPUTNIC study, including 63 from Besancon and 58 from Basel. Self-reported wireless phone use and screen time were sporadically associated with visuo-spatial and verbal cognitive performance, compatible with chance findings. We found a small but robust significant increase in stress 0.03 (0.00–0.06; on a 1–10 Likert-scale) in relation to a 10-min increase in mobile phone screen time. Sleep duration and quality were not associated with either cordless or mobile phone calls, or with screen time.
Discussion: The study did not find associations between short-term RF-EMF markers and cognitive performance, HRQoL, or sleep duration and quality. The most consistent finding was increased stress in relation to more screen time, but no association with cordless or mobile phone call time.

1. Introduction

Concerns that exposure to radiofrequency electromagnetic fields (RF-EMF) may lead to health effects have reemerged with the recent introduction of 5G deployment. While environmental contributions from base stations and radio masts contribute to personal exposure, most of the dose experienced by the general population is a direct result of near-field sources, such as mobile phones, laptops, tablets, WiFi and cordless phones which are used close to the body (Cabré-Riera et al., 2020; van Wel et al., 2021; Eeftens et al., 2023). Due to high output and

Abbreviations: 95% CI, 95% Confidence interval; HRQoL, Health-related quality of life; RF-EMF, radio-frequency electromagnetic fields; WiFi, Wireless Fidelity.

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proximity to the head during phone calls, the head and brain have been identified as target tissues by several key studies (Calderón et al., 2022). Nevertheless, previous reviews concluded there was a lack of evidence for negative influences of RF-EMF on attention and cognitive function (Valentini et al., 2010; Barth et al., 2012; Curcio, 2018, Ishihara, Yamazaki et al. 2020). Because of this, the World Health Organization (WHO) has recently identified cognitive function, sleep and several health-related quality of life symptoms as priority topics for systematic review (Röösli et al., 2021; Verbeek et al., 2021; Benke et al., 2022; Bosch-Capblanch et al., 2022).

Cognitive function is typically considered as a mental process that involves a range of domains including learning, memory, reasoning, problem solving, decision making and attention (Benke et al., 2022). Several previous research studies have observed effects on cognitive function in association with localized exposure of the head to radio frequency electromagnetic fields (RF-EMF) (Curcio, 2018, Ishihara, Yamazaki et al. 2020). The real-life short-term implications on cognitive performance and health-related quality of life have not been well studied. A recent study from Switzerland found indications that high EMF exposure is negatively associated with figural visuo-spatial skills, which are processed on the right side of the brain, but not verbal skills, located on the left side (Schoeni et al., 2015). This finding was replicated in an independent sample (Foerster et al., 2018), and is currently evaluated in a cohort of adolescents from the UK (Toledano et al., 2019).

Several studies have previously looked at RF-EMF exposure in relation to non-specific physical symptoms like headaches, dizziness, concentration difficulties and anxiety. In randomized double-blind human experimental studies, mostly no acute effect of RF-EMF exposure was observed in general population samples or in individuals stating to react to EMF (Schmiedchen et al., 2019). In epidemiological studies and population surveys, extensive mobile phone and/or e-media use was often found to be related to reduced HRQoL including a wide range of symptoms including behavioural problems, hearing loss, headaches, fatigue, concentration and stress (Chetty-Mhlanga, Fuhrimann et al. 2020). Yet, studies targeted to separate biophysical effects from RF-EMF exposure from other non-physical related pathways such as addiction or night-time use indicate that RF-EMF exposure is the least likely cause (Roser et al., 2016; Schoeni et al., 2016; Schoeni et al., 2017, Auvinen, Feychting et al. 2019, Guxens, Vermeulen et al. 2019)

Regarding effects on sleep, several studies -rather consistently-point to changes in the electroencephalogram (EEG) alpha frequency range, both awake (Danker-Hopfe et al., 2019; Wallace and Selmaoui, 2019) and while asleep (Regel et al., 2007) associated with RF-EMF exposure. It is possible that such changes could affect working memory and memory consolidation (Frenda and Fenn, 2016). Nevertheless, many studies so far indicated no association between RF-EMF exposure and self-reported sleep quality (Tettamanti et al., 2020).

The SPUTNIC study (Study Panel on Upcoming Technologies to study Non-Ionizing radiation and Cognition) aimed to investigate the association between exposure to RF-EMF resulting from the use of mobile phones and cognitive performance (verbal as well as visuo-spatial skills), health-related quality of life and sleep quality, which are potentially associated with these exposures. We aim to see if we can reproduce the association between RF-EMF exposure and visuo-spatial skills (Schoeni et al., 2015, Foerster et al., 2018). We will further investigate whether we find a similar amplified association looking at right-handed individuals, as was found in previous studies (Schoeni et al., 2015, Foerster et al., 2018), and whether the opposite is –again-true for verbal skills. This paper describes the results of a panel study in 121 adults on RF-EMF exposure markers and cognitive performance, as assessed through six innovative “game-like” tasks, which each of the participants completed repeatedly.

2. Methods

The SPUTNIC panel study gathered data from smartphone users in Basel (Switzerland) and Besancon (France), following each participant for 10 days. We repeatedly obtained data on cognitive function and phone use (cordless and mobile call duration and screen time) from the group of volunteer participants between September 2019 and January 2021.

2.1. Inclusion and exclusion criteria

We included adults, between 18 and 70 years old, who used a smartphone regularly, had access to a desktop, laptop, or tablet computer with internet access, spoke fluent German (Switzerland) or French (France), and lived within 30 min commuting time from one of the study centers in Basel and Besancon. We strived for an equal representation of males and females. We excluded participants with visual or hearing loss, those with insufficient language skills or physical, mental or neurological disorders which would make it impossible to complete the tests and questionnaires (e.g. head trauma, stroke, neurodegenerative pathologies, epilepsy, multiple sclerosis, dyslexia, attention deficit hyperactivity, major depression, schizophrenia, bipolar disorder). We also excluded people who were not able/willing to abstain from using psychoactive/recreational drugs for the duration of the study. We further excluded people working night shifts and pregnant persons beyond the 7th month, in order to minimize the risk of premature drop-out. Participants were not asked whether they thought that any of the RF-EMF exposure markers affected any of the health endpoints studied.

2.2. Recruitment of participants

In Switzerland, the study was advertised through printed flyers, among relatives, friends and family of the researchers, on the online platform of Basel University, and as unpaid posts on Facebook, Instagram and Twitter, and in the popular free “20 Minutes” newspaper. In France, the study was advertised through printed posters, and communications in regional and local newspapers, radio and TV. In total, 153 + 145 people showed initial interest in the study (in Switzerland and France, respectively), and after determining eligibility, ultimately 121 were recruited into the study (see Table 1 for recruitment overview). All recruitment took place between July 8, 2019 and December 14, 2020 (Basel) and between October 30, 2019 and December 14, 2020 (Besancon).

2.3. Home visits

All interested participants were contacted by phone and screened for eligibility. If they agreed to take part in the study, a study assistant visited them to explain the study, obtain informed consent, and introduce the different parts of the study. In addition, the participants then independently completed an intake questionnaire on a study tablet, about their education and employment, general use of mobile communication technologies, handedness, general health situation and medical history, cell phone dependence (e.g. addiction), lifestyle and physical activity.

Subsequently, the study assistant explained the daily assessments in which the participant would take part in over the next 14 days, in order to assess 1) cognitive performance, 2) health-related quality of life (HRQoL), and 3) sleep duration and quality. Participants were asked to complete ten daily assessments within 14 days (allowing them to take the weekends off). The equipment was then collected 14 days later again by the study assistant.

2.4. Daily assessments and health endpoints measured

In order to investigate the associations between phone use and the three main health outcomes (cognitive performance, HRQoL and sleep duration & quality), study participants completed daily assessments in the early evenings (6–10PM) including cognitive testing, a short

Table 1
Characteristics of the study population by study center.

	Total	Besancon, FR	Basel, CH	P-value
	121	63	58	
Age [years] (mean (SD))	34.3 (15.5)	31.4 (13.4)	37.4 (17.0)	0.034 [b]
Male sex (n (%))	36 (30)	15 (24.2)	21 (36.2)	0.217 [c]
Height [cm] (mean (SD)	169 (8.0)	168 (7.2)	170 (8.7)	0.343 [b]
Weight [kg] (mean (SD))	65.5 (14.3)	65.4 (16.0)	65.7 (12.5)	0.898 [b]
Education status (n (%)) [a]				0.050 [c]
ISCED2	1 (0.8)	0 (0)	1 (1.7)	
ISCED3	33 (27.3)	11 (17.5)	22 (37.9)	
ISCED45	16 (13.2)	12 (19.0)	4 (6.9)	
ISCED6	38 (31.4)	20 (31.7)	18 (31.0)	
ISCED7	28 (23.1)	18 (28.6)	10 (17.2)	
ISCED8	5 (4.1)	2 (3.2)	3 (5.2)	
Employment status (n (%))				0.167 [c]
Employed	50 (41.3)	29 (46.0)	21 (36.2)	
Student	46 (38.0)	21 (33.3)	25 (43.1)	
Pensioner	13 (10.7)	4 (6.3)	9 (15.5)	
Unemployed	9 (7.4)	7 (11.1)	2 (3.4)	
Other	3 (2.5)	2 (3.2)	1 (1.7)	
Right-handed (n (%))	106 (87.6)	55 (87.3)	51 (87.9)	1.000 [c]
Hand phone use (n (%))				0.523 [c]
Both (n (%))	50 (41.3)	25 (39.7)	25 (43.1)	
Left (n (%))	21 (17.4)	9 (14.3)	12 (20.7)	
Right (n (%))	50 (41.3)	29 (46.0)	21 (36.2)	
Cordless calls [min] (median; IQR) [d]	0 (0–2.7)	0.04 (0–4.5)	0 (0–1.3)	0.110 [e]
Mobile calls [min] (median; IQR) [d]	3.0 (0.5–8.8)	4.3 (0.1–9.0)	3.0 (1.0–8.3)	0.746 [e]
Screen time [min] (median; IQR) [d]	40.0 (24.5–68.8)	47.0 (36.2–76.7)	28.0 (22.2–53.8)	0.005 [e]
Total time [min] (median; IQR) [d]	46.5 (30.0–76.8)	55.5 (40.3–87.0)	35.5 (25.5–64.8	0.008 [e]

[a] Education status was categorized following the "International Standard Classification for Education" (ISCED) with categories 2 = Lower secondary education, 3 = Higher secondary education, grammar school; 45 = Post-secondary, non-tertiary education; 6 = Bachelor, University or teacher's college or equivalent; 7 = Master, University or teacher's college or equivalent; 8 = Doctorate, University.
[b] Linear Model ANOVA.
[c] Fisher's exact test.
[d] These exposures were assessed daily and repeatedly for each participant. We present a median and interquartile range (IQR) of personal mean cordless call time, mobile call time and screen time.
[e] Wilcoxon rank sum test (non-parametric because non-normal distribution).

questionnaire, and the continuous measurement of sleep duration and quality. We chose the time point of assessments in the evening time because a standardized time slot allowed us to limit within-person variability in the outcome due to the time of the day, and in order to accommodate most participants had day jobs and were not able to perform the assessments during the day.

2.4.1. Cognitive performance

We assessed cognitive performance every evening by asking the participants to complete a test battery consisting of six quick "game-like" tests, of which three focused on verbal, and three focused on spatial skills (Online Supplement (OS) Fig. 1). Participants received a unique personal link to the test battery and were asked to complete the assessment at approximately the same time every day over 10 days, using a tablet or home computer. The whole test battery took approximately 15–20 min to complete each evening. Participants were asked to complete these assessments during the evening, first taking the HRQoL questionnaire, and then completing the cognitive test battery.

All tests were based developed in collaboration with Cambridge Brain Sciences, and translated into both German (Basel, Switzerland) and French (Besancon, France), to allow participants to take them in their native language. The tests themselves were identical to or similar to widely used and well-validated cognition tests such as the Stroop Colour-Word Test (for executive functions) (Batchelor et al., 1995), and the Corsi block tapping test (for working visuo-spatial memory) (Corsi, 1972), but were administered in a digital format for increased standardization and reproducibility, and in order to record reaction time. Three tests were mainly focused on verbal skills (predominantly left side of the brain), and three mainly focused on visuo-spatial skills (predominantly right side of the brain). We recognize that all tests in reality require more than one function, which can often not be mapped to any single brain region. (Cambridge Brain Sciences, 2022) OS Fig. 1 shows test instructions and screenshots the final test battery, consisting of the six tests which were each administered to SPUTNIC participants 10 times. Participants reported liking the short "game-like" nature of the tests, which made them suitable for repeated (daily) use.

2.4.2. Health-related quality of life and daily mini-questionnaire

HRQoL was assessed on a daily basis by a short online mini-questionnaire (5 min), which the participants would complete every day in a browser. This daily mini-questionnaire collected data on.

- HRQoL and well-being (e.g. fatigue, mood, stress) at the present moment (when answering the questionnaire);
- Exposure-related variables (e.g. looking at the phone within 1 h of going to bed the previous night, cordless phone use in the last 4 h, and mobile phone call duration and screen time during the last 4 h);
- Important time-varying confounders: (e.g. time spent outdoors, coffee and alcohol intake).

2.4.3. Sleep duration and quality

Sleep duration and quality were measured continuously using a Fitbit Inspire activity tracker. This is a small wrist-worn device, which is commercially available and can measure the duration, efficiency and stages of sleep (awake, light, deep and REM). In addition, it registers the number of steps the wearer takes throughout the day. During the first home visit by the study assistant, participants provided the information needed to set up a Fitbit Inspire activity tracker (birth year, sex, height and weight). The study assistant set up the Fitbit application on the participant's phone and configured their personal Fitbit account. We retrieved daily sleep duration and stages data for each account via an Application Programming Interface (API). Sleep efficiency was calculated as the time asleep divided by the total time spent in bed * 100%.

2.5. Exposure assessment

Daily markers of RF-EMF exposures were collected in the daily questionnaire, during which participants were asked about their call time on cordless phones (in minutes), their total mobile phone call time (in minutes) and their total mobile phone screen time (in minutes) in the 4 h prior to the current assessment, giving an indication of the exposure through the own use of mobile phones. Previous research showed that DECT calls, mobile calls and mobile phone data use are the predominant contributors to personal RF-EMF exposure (Cabré-Riera et al., 2020; van Wel et al., 2021; Eeftens et al., 2023), and therefore the best exposure markers for RF-EMF which could be feasibly and repeatedly assessed. We chose 4 h as a typical maximum time frame for short-term human laboratory studies (Bosch-Capblanch et al., 2022). Screen time related specifically to screen time on a smartphone, not including other devices such as laptops or televisions. Laterality of phone use while calling was assessed by questionnaire in the intake questionnaire during the first home visit.

2.6. Statistical handling

2.6.1. Cognitive performance

Test scores were calculated for each participant, for each day, and for each of six cognitive tests (focussed on either left or right brain tasks). We calculated normalized the test scores in order to be able to present all tests on the same scale, and to enable the combined analysis of the three verbal tests, and similarly for the three visuo-spatial tests. Normalized scores were calculated by subtracting the test-specific average score and dividing by the test-specific standard deviation. We expressed all associations as a percentage change in normalized test scores. The scores for the six individual tests, as well as all visuo-spatial and all verbal tests combined were modelled as a function of the three exposure markers, which the participant experienced prior to taking the test. We adjusted for coffee and alcohol consumption, time spent outside, type of day (workday/non-workday), sleep duration the night before and the learning effect after completing the tests multiple times, following a cubic b-spline trend. We studied the association between the three markers of RF-EMF exposure verbal and visuo-spatial performance. In addition, we stratified the analysis for participants who used their phone on the right side, and those who used their phone on the left side or on both sides, and thus experienced exposure from calls primarily on the different sides of the head.

2.6.2. Health-related quality of life

Scores related to sleepiness, stress and mood were all assessed and analysed on a continuous scale between 1 and 10, as a function of the three RF-EMF exposure markers, adjusting for coffee and alcohol consumption, time spent outside, type of day (workday versus non-workday), sleep duration the night before.

2.6.3. Sleep duration and quality

Sleep duration and efficiency were evaluated on a continuous scale as a function of the three RF-EMF exposure markers. We adjusted for time-varying confounders coffee and alcohol consumption and time spent outside the day before and type of day (workday/non-workday).

2.6.4. Mixed modelling

For all outcomes (cognitive performance, HRQoL and sleep) we considered the data from all participants who completed at least three assessments on three different days. We analysed the association between each of the three markers of RF-EMF exposure on three endpoints using a mixed modelling approach, adjusting for age and sex, and with random intercepts for each individual, thereby taking into account the systematic differences between individuals in cognitive performance, HRQoL and sleep habits. We chose a linear approach considering there is no established dose-response relationship, between the exposure and any of the evaluated health outcomes, and as such no indication for threshold effects, plateaus, or other non-linear behavior that would justify choosing a more complicated (and likely less interpretable) model. We considered that there might be a substitution effect (where participants can only engage in a single exposure related activity at any one time (cordless phone calls, mobile phone calls, or screen time). In addition, we therefore analysed the associations with all phone calls, and of the sum of all three exposure markers. All data compilation, management and analyses were done in R Version 4.0.3 (R Core Team, 2013). Mixed models were fitted using the R lme4 package with random intercepts for each study participant for all three outcomes.

3. Results

A total of 121 participants completed the study: 63 in Besancon and 58 in Basel. Table 1 shows an overview of their characteristics and the distribution of exposure metrics. Correlations between different exposure metrics are shown in OS Fig. 2A, day-to-day variability is shown in OS Fig. 3. Participants from Basel were slightly older on average, but otherwise the populations did not differ significantly between the study centers regarding personal characteristics. In terms of exposure, Besancon participants experienced significantly more screen time than Basel participants.

3.1. Associations with cognitive performance

Out of 121 participants, 101 completed the cognitive assessment at least three times, and had complete exposure and confounder information available (including sleep quality). Most people completed the cognitive assessment 10 times (as instructed), with a range of anywhere between 3 and 14 times, resulting in a total of 5198 observations for all six cognitive tests combined. Scores from the different tasks showed low to moderate positive correlations, indicating that those who did well on a certain task, were likely to do well on the other tasks also (OS Fig. 2B). Personal means were normally distributed with the exception of the “Rotations” task (due to a single outlier). See also OS Fig. 4. Table 2 shows the average and standard deviation of the scores for each test and OS Fig. 5 shows their performance as a function of the assessment number. This shows that there was a minor improvement in test performance with every subsequent assessment (learning effect), and that this improvement was generally greater during the first few assessments, followed by a plateau, which we adjusted for by a cubic spline. Older adults scored slightly (though significantly) worse on all tasks except the “Digit Span” task. Males scored slightly better on the “Double Trouble” task than females, but the overall picture was balanced; females scored slightly (though not significantly) higher in the digit span and grammatical reasoning tests.

Fig. 1 and OS Table 1 show the associations between the different exposure markers for the 4 h prior to taking the tests, and their association with the score of each test, as well as all three verbal and all three visuo-spatial tests combined. Out of 24 statistical tests for all participants with adjustment for time-varying confounders, two significant associations were observed. For a 10-min increased duration of cordless calls: a −0.16 (95% CI: −0.30, −0.02) change in the normalized test score for the Rotations task. In addition, we found a 0.04 (95% CI: 0.01, 0.08) increase for the normalized Spatial span task test score for a 10-min increase in duration of mobile phone calls. There were no substantial differences with the non-adjusted estimates (Fig. 1). The association for the Rotations task tended to be slightly stronger when restricted to participants who used their phones on the right side only, but the Spatial span association was no longer significant.

In 72 laterality-stratified statistical tests for phone use on the right versus, on both sides, or on the left, we observed ten significant associations (Fig. 1). For right-side users, we found a −0.21 (95% CI: −0.42, 0) decrease in the normalized test scores for the Rotations task associated with cordless phone calls, and a 0.05 (95% CI: 0, 0.09) increase for all visuo-spatial tests associated with mobile phone calls (OS Table 1). Among those who reported using their phones with both hands, we found a −0.04 (95% CI: −0.08, 0) decrease in test score for the Double Trouble task associated with mobile phone calls, and a −0.29 (95% CI: −0.53, −0.04) decrease in test score for the Spatial Span task with increased cordless calls. Within this group, we also found that an increase in screen time was associated with increases in test score of 0.01

Table 2
Mean (Standard deviation) of test scores for the six different cognitive tests.

Cognitive skill[a]	Test	Mean [b] (Standard deviation)
Verbal	Digit Span	7.0 (1.1)
	Double Trouble	50 (13)
	Grammatical Reasoning	18.8 (4.7)
Visuo-Spatial	Odd One Out	11.7 (2.1)
	Rotations	132 (34)
	Spatial Span	6.2 (0.9)

[a] For details on each test, see OS Fig. 1.
[b] Presented are the means and standard deviations of 114 personal means.

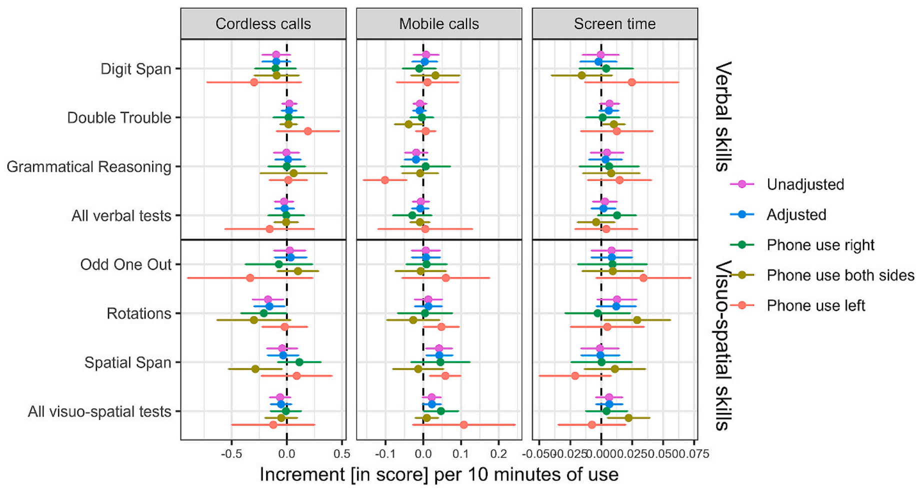

Fig. 1. Association between RF-EMF exposure markers[a] and normalized cognitive performance, for unadjusted[b] (n = 101), adjusted[b] (n = 101), and stratified for those who use their phone on the right[b] (n = 39), those who use their phone on both sides[b] (n = 45) and those who use their phone on the left (n = 17)[b].
[a] All associations are expressed as percentage change in normalized test scores per 10-min increase of respective exposure markers (cordless and mobile phone calls, screen time). Numeric associations and 95% confidence intervals are reported in OS Table 1. Note that these associations were fitted on normalized test scores with a mean of 0 and a standard deviation of 1.
[b] All associations were adjusted for learning effect, age and sex. The "Adjusted", "Phone use right", "Phone use both sides" and "Phone use left" associations were additionally adjusted for coffee and alcohol consumption, type of day (workday or non-workday), time spent outside and total sleep duration.

(95% CI: 0, 0.02), 0.03 (9% CI: 0, 0.06) and 0.02 (95% CI: 0.01, 0.04) for the Double Trouble, Rotations and all visuo-spatial tests, respectively. We further found a decrease of −0.10 (95% CI: −0.16, −0.05) in test score for the Grammatical reasoning task, an increase of 0.05 (95% CI: 0, 0.09) for the Rotations task, and an increase of 0.06 (95% CI: 0.02, 0.10) for the Spatial span task, all associated with mobile phone calls, among the 17 participants reported using their phones exclusively on the left. When we summed duration of exposure for both cordless and mobile phone calls, or for all three RF-EMF exposure markers, results were similar those observed for the three outcomes separately, but attenuated (OS Table 1).

4.2. Associations with health-related quality of life

Table 3 presents the distribution of scores (1–10) related to fatigue, mood and stress. Out of 121 participants, 105 participants completed at least three daily questionnaires about their health-related quality of life, as well as sleep registration (confounder), totaling 918 assessments. Scores from the different HRQoL assessments showed a low correlation, where fatigue and stress were positively correlated with each other, and negatively correlated with mood (OS Fig. 2C). OS Fig. 6 shows the development of daily scores of HRQoL. Mood was significantly worse on workdays, compared to non-workdays (−0.44 (95% CI: −0.71, −0.17)) and people felt more fatigued (0.46 (95% CI: −0.16, 0.76)). Males also reported lower levels of fatigue (−0.90 (95% CI: −1.54, −0.25)) and stress (−1.40 (95% CI: −2.07, −0.72)) than females. Spending time outside was associated with an increased mood 0.019 (95% CI: 0.006, 0.032) per increment of 10 min outside time.

We did not see associations between cordless or mobile phone calls and any of the HRQoL indicators, but found a reduction of −0.03 (95% CI: −0.07, 0.00) in fatigue and a reduction of −0.03 (95% CI: −0.06, 0.00) in the mood people reported for an increment of 10 min of additional mobile phone screen time they reported during the 4 h prior to filling in the questionnaire (Fig. 2), although neither was strictly statistically significant. Moreover, their stress increased by approximately the same number of points: 0.03 (95% CI: 0.00, 0.06), which was statistically significant. The association found for the combined exposure to cordless and mobile calls were similar to that found for mobile calls, but attenuated. Similarly, we found attenuated associations for all three RF-EMF exposure markers combined, similar to those found for screen time (OS Table 2).

Table 3
Health-related quality of life scores[a] of the study population by study center.

	Total	Besancon, FR	Basel, CH
N	105	51	54
Fatigue	5.44 (1.42)	5.55 (1.27)	5.33 (1.55)
Mood	7.22 (1.19)	7.07 (1.08)	7.37 (1.28)
Stress	3.43 (1.52)	3.46 (1.55)	3.40 (1.51)

[a] HRQoL was assessed as three separate questions, asking participants to rate their level of fatigue on a scale from 1 (no fatigue) to 10 (extreme fatigue), mood from 1 (very bad mood) to 10 (very good mood), and stress from 1 (no stress) to 10 (extreme stress).

4.3. Associations with sleep duration & quality

Out of 121 participants, 105 participants registered at least 3 and up to 13 nights of sleep, totaling 918 nights. Table 4 shows the total time in bed, total time asleep, sleep efficiency, and the duration of the four sleep stages (deep, light, REM and awake). Sleep duration and quality metrics were generally positively correlated with each other, except for the duration lying awake (versus all other metrics) and the duration of deep sleep versus light sleep (OS Fig. 2D), and OS Fig. 7 shows the day-to-day variability by assessment number. Compared to women, men spent less time asleep (−21 min (95% CI: −43, −6 min), and had reduced sleep efficiency (−1.3% (95%-CI: −2.1%, −0.4%)) and REM sleep (−11.0% (95% CI: −21.4%, −0.6%)). Participants spent 0.30 min (95% CI: 0.16, 0.45 min) more lying awake with each year they aged.

Fig. 3 shows the associations between the various sleep outcomes listed and self-reported phone use the day before. We did not find any consistent directions of effect or significant associations across the different exposure markers or outcomes. Adjusted and unadjusted effect estimates were very similar (Fig. 3), and no associations were found either when we summed duration of exposure to cordless and mobile phone calls, or all three exposure markers (OS Table 3).

5. Discussion

The study did not find associations between short-term markers of RF-EMF exposure and cognitive performance, HRQoL, or sleep duration and quality.

We only found sporadic significant associations between the RF-EMF exposure markers and cognitive performance. The significant associations we found between phone use and cognitive function were not consistent across multiple cognitive tests, and can likely be attributed to chance considering the many associations tested. The effect sizes reported were generally small and not consistent across the three verbal or the three visuo-spatial tasks. Using a significance level of 0.05 as done in

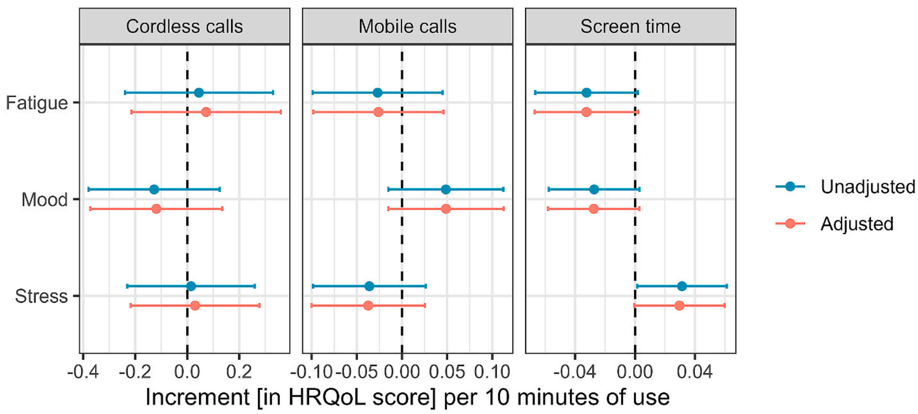

Fig. 2. Unadjusted and adjusted[a] (n = 105) associations between RF-EMF exposure markers[b] and HRQoL[c].
[a] All associations result from a mixed model with random effects for participant, and are reported per 10-min increment of respective exposure markers (cordless and mobile phone calls, screen time) and were adjusted for age and sex. The "Adjusted" associations were additionally adjusted for coffee and alcohol consumption, type of day (workday or non-workday), time spent outside and total sleep duration.
[b] All associations are expressed as change in absolute HRQoL scores per 10-min increase of respective exposure markers (cordless and mobile phone calls, screen time). Numeric associations and 95% confidence intervals are reported in OS Table 2.
[c] HRQoL was assessed as three separate questions, asking participants to rate their level of fatigue on a scale from 1 (no fatigue) to 10 (extreme fatigue), mood from 1 (very bad mood) to 10 (very good mood), and stress from 1 (no stress) to 10 (extreme stress).

Table 4
Sleep habits of the study population by study center.

	Total	Besancon, FR	Basel, CH
N	105	51	54
Total time in bed [min] (mean (SD))	483 (44)	484 (40)	482 (48)
Total time asleep [min] (mean (SD))	422 (41)	422 (39)	422 (43)
Sleep efficiency [%] (mean (SD)) [a]	88 (2)	87 (2)	88 (2)
Time in deep sleep [min] (mean (SD))	78 (18)	77 (17)	78 (18)
Time in light sleep [min] (mean (SD))	274 (33)	272 (24)	276 (40)
Time in REM sleep [min] (mean (SD))	93 (22)	95 (26)	91 (18)
Time awake [min] (mean (SD))	38 (10)	38 (10)	38 (11)

*P-value refers to the significance of the difference between the Besancon and the Basel populations, based on linear model ANOVA.
[a] Sleep efficiency was calculated as the time asleep divided by the total time in bed * 100%.

this study, one would expect 4.8 significant associations out of 160 conducted statistical tests (5 exposures, 8 cognitive tasks, full group and right, both and left side users), which fits well the observed fourteen significant results (of which 5 adverse, and 9 protective), OS Table 1.

Previous work found consistently that phone use on the right was associated with a decrease in spatial memory, and phone use on the left (or both hands) was associated with a decrease in verbal memory (Schoeni et al., 2015, Foerster et al., 2018). This study did not confirm a similar pattern. There were fourteen associations in agreement with this pattern and ten contradicting it, most non-significant (Fig. 1, OS Table 1). Similar studies also reported no or heterogeneous effects, both on the long-term (Cabré-Riera et al., 2021) and on the short-term in controlled exposure settings (Verrender et al., 2016; Vecsei et al., 2018).

We found that increased screen time was associated with a small tentative decrease in mood and fatigue, and a significant increase in self-reported stress level, consistent with previous studies (Cain and Gradisar, 2010, Davies et al., 2012; Lacy, Allender et al. 2012; Tang et al., 2021). While the effect size per 10-min increment was small, we note that the typical interquartile range contrast is much larger for screen time than for calls (either cordless or mobile). On average, participants spent 40 min (IQR 24.5–68.8 min) looking at the screens of their phones within the 4 h prior to assessment. The effect of an interquartile range increment in exposure is therefore accordingly larger. Interestingly, no such effect was present for either cordless or mobile phone calls. Similar effects of screen time on HRQoL, especially in combination with lack of physical activity have been shown also in previous studies (Davies et al., 2012; Lacy, Allender et al. 2012). In line with these studies, we noticed a significant increase in mood when people reported spending more time outside that day. However, we note that surfing the web on the mobile phone (usually while connected to a WiFi connection), generates relatively little RF-EMF exposure compared to calls. Given the absence of association for calls involving higher levels of RF-EMF exposure, it is therefore unlikely that such an association with screen time results from RF-EMF exposure, and suggests a non-biophysical mechanism.

In terms of non-biophysical pathways, various different operating mechanisms are discussed. For instance, it has been postulated that e-media use in adolescents may result in less physical activity (Edelson et al., 2015), increased night time eating (Cha et al., 2018), higher body mass index (BMI) (Fatima et al., 2015), and media addiction (Samaha and Hawi, 2016); and any of these mechanisms may interact with the

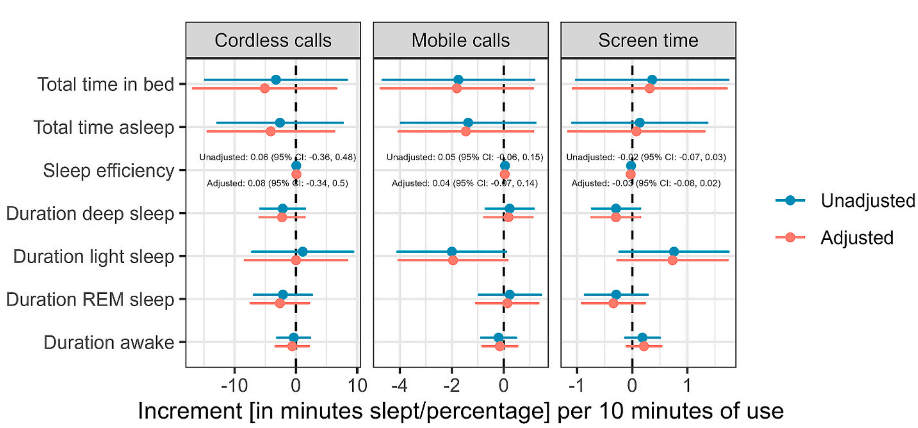

Fig. 3. Unadjusted and adjusted[a] (n = 105) associations between RF-EMF exposure markers[b] and sleep outcomes[c].
[a] All associations result from a mixed model with random effects for participant and are reported per 10-min increment in phone use and were adjusted for age and sex. The "Adjusted" associations were additionally adjusted for coffee and alcohol consumption, type of day (workday or non-workday), and time spent outside.
[b] All associations are expressed as change in absolute sleep scores per 10-min increase of respective exposure markers (cordless and mobile phone calls, screen time). Numeric associations and 95% confidence intervals are reported in OS Table 3.
[c] All outcomes were measured in minutes, except for sleep efficiency, which is defined as the time asleep divided by the total time in bed * 100%.

HRQoL or cognitive functions. An alternative explanation is an influence from sleep deprivation through longer waking hours due to the time spent on the devices, and consecutive delayed sleep onset (Van den Bulck, 2007), which then may impair cognitive performance and cause symptoms such as fatigue and exhaustion. We adjusted for sleep duration of the previous night but cannot rule out an impact from chronic sleep deprivation not captured by day-to-day variation. Sleep quality might also be impaired as a result of the psychological and somatic arousal and cognitive over-activation through the media content (Cain and Gradisar, 2010). We evaluated stress as an outcome, but cannot exclude that it may be (in addition) a mediator or moderator for unmeasured effects or other endpoints. Due to small sample size, we were not able to perform these analyses formally.

We did not find any consistent associations between markers of RF-EMF exposure and sleep duration and quality. This is consistent with several other previous studies, which have noted differences in EEG (Curcio et al., 2005; Regel et al., 2007), but no reduction in sleep duration or quality (Regel et al., 2007; Eggert et al., 2020).

Strengths of the study include its repeated study design and the high number of repeated observations per individual, which allowed us to study the day-to-day variability both in exposure and the various health endpoints, on the short term. Even if we have high temporal resolution, reverse causality or a “vicious spiral” effect cannot be excluded. Indeed, worse mood and higher stress level may have preceded and resulted in more time spent in front of the screen, possibly causing further mood decline and stress, and so on.

A limitation of the study include its relatively small sample size of 121 individuals, which is further reduced to 101 or 105 by missing data for exposure and time-varying confounders for the different outcomes. We performed a priori power calculations assuming cognitive effects similar to those found by Foerster et al. (2018) (Foerster et al., 2018), who found a 2.6% decrease in verbal memory and a 3.9% decrease in spatial memory for an interquartile range (IQR) increase in exposure. We further assumed similar exposure contrasts and a learning effect of 2% over 10 days, which indicated that a minimum of 100 participants would be needed to reach 80% power. While the recruitment target was reached, the study may still have been underpowered to detect possible effects smaller than those assumed in the power calculation. We note that we analysed repeated observations, which increases the statistical power compared to a conventional analysis of between-subject variability. The small sample size, however, may be a limitation for the generalizability of our findings. While we found sporadic significant associations with the RF-EMF exposure markers, these were few in number and not consistent across multiple cognitive tests or between different exposure markers. Given that false positive rate is 5%, six significant findings among 72 associations between exposure and cognitive test results and zero significant associations among 21 sleep analyses are compatible with chance findings. Nevertheless, despite the small sample size, the finding of a significant adverse association between screen time and stress, and tendencies towards a worse mood and reduced fatigue (although not significant) make associations between screen time and HRQoL less likely to be due to chance findings.

Another limitation is exposure misclassification: we have a good idea about day-to-day variability in exposure due to cordless phone calls, mobile phone calls and data traffic using the own mobile phone, we acknowledge that there are other sources of RF-EMF radiation which were not assessed as part of this study (e.g. environmental sources, and usage of personal communication devices such as tablets and laptops, televisions). It was not feasible to assess exposure in real-time, or ask participants on a daily basis about multiple time frames of exposure, side of use, distance to the head, hands-free use, for all possible devices. Our choice to assess RF-EMF exposure metrics in the 4-h period prior to health assessments was based on the maximum time frame typical human laboratory studies on short-term effects have considered (Bosch-Capblanch et al., 2022). We acknowledge that there is no established lag time for the effect’s onset, or typical duration of effect, which may have resulted in bias to the mean (explaining a lack of effect). In addition, duration of calls and screen time are likely to be crude proxies of the actual RF-EMF dose (Calderón et al., 2022), which further depends on the connectivity, as well as phone characteristics (e.g. Specific Absorption Rate) and the frequency of the used service (Mazloum, Aerts et al. 2019). However, recent research based on measurements and exposure models have shown that mobile phone calls are still by far the largest source of personal exposure (Roser et al., 2015), particularly exposure to the head, so it is unlikely that this would have resulted in large and systematic misclassification. We relied on self-reported use, which is subject to some uncertainty. However, to estimate duration of use for the last 4 h is substantially less demanding than life-time use as requested in epidemiological studies on long term effects. Moreover, since exposure information was provided before doing the test and knowing the test performance, we do not expect differential exposure misclassification.

6. Conclusion

We aimed to measure the association between daily markers of RF-EMF exposure (within 4 h prior to outcome assessment) and three distinct short-term health outcomes: cognitive performance, HRQoL and sleep duration & quality, by performing daily assessments of both in a group of adult volunteers. Inconsistent findings for cognitive test and absence of associations for sleep outcomes are in line with other studies so far, and also the effects of screen time on various HRQoL have previously been indicated.

Credit author statement

Marloes Eeftens: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. Sophie Pujol: Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. Aaron Klaiber: Methodology, Investigation, Data curation, Writing – review & editing. Gilles Chopard: Conceptualization, Writing – review & editing, Funding acquisition. Andrin Riss: Methodology, Writing – review & editing. Florian Smayra: Data curation. Benjamin Flückiger: Methodology, Writing – review & editing. Thomas Gehin: Investigation, Data curation, Writing – review & editing. Kadiatou Diallo: Formal analysis, Writing – review & editing. Joe Wiart: Conceptualization, Validation, Writing – review & editing. Taghrid Mazloum: Validation, Writing – review & editing. Frédéric Mauny: Conceptualization, Writing – review & editing, Funding acquisition. Martin Röösli: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition

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Ethics

Ethical permission for the Swiss (Basel) part of the panel study was granted by the Ethical Commission Northwest/Central Switzerland on March 25, 2019 (EKNZ number 2019–00466). For the French part (Besançon), the study has been registered by the Clinical Research and Innovation Delegation of the University Hospital of Besançon under the number P2019-447. Data were collected and treated by a team of the University Hospital, observing the European General Data Protection Regulation (GDPR), in accordance with the French Data Protection Authority (CNIL) reference methodology #004 (MR-004: Research not involving the human being, studies and evaluations in the health field). The university hospital center of Besançon has signed a commitment to comply with the CNIL's reference methodologies. All the participants included in the study received written information and had sufficient time for reflection to allow them to stipulate their opposition to the collection and processing of their data.

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.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116011.

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