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Does acute radio-frequency electromagnetic field exposure affect visual event-related potentials in healthy adults?

Anna Dalecki
University of Wollongong, *Monash University*, adalecki@uow.edu.au

Sarah P. Loughran
University of Wollongong, loughran@uow.edu.au

Adam Verrender
University of Wollongong, av138@uowmail.edu.au

Catriona A. Burdon
University of Wollongong, cburdon@uow.edu.au

Nigel A.S. Taylor
University of Wollongong, ntaylor@uow.edu.au

See next page for additional authors

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Results: P1 amplitude was reduced ($p = .02$) and anterior N1 latency was increased ($p = .04$) during Exposure compared to Sham. There were no effects on any other ERP latencies or amplitudes. Conclusions: RF-EMF exposure may affect early perceptual (P1) and preparatory motor (anterior N1) processes. However, only two ERP indices, out of 56 comparisons, were observed to differ between RF-EMF exposure and Sham, suggesting that these observations may be due to chance.

Significance: These observations are consistent with previous findings that RF-EMF exposure has no reliable impact on cognition (e.g., accuracy and response speed).

Disciplines
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Authors
Anna Dalecki, Sarah P. Loughran, Adam Verrender, Catriona A. Burdon, Nigel A.S. Taylor, and Rodney J. Croft

Does Acute Radio-Frequency Electromagnetic Field Exposure Affect Visual Event-Related Potentials in Healthy Adults?

Anna Dalecki [a, b], Sarah P. Loughran [a,c], Adam Verrender [a,c], Catriona A. Burdon [d], Nigel A. S. Taylor [c,d], Rodney J. Croft [a,b,c]

[a] School of Psychology; Illawarra Health & Medical Research Institute, University of Wollongong, Australia;

[b] Population Health Research on Electromagnetic Energy, Monash University, Melbourne, Australia

[c] Australian Centre for Electromagnetic Bioeffects Research, Wollongong, Australia;

[d] Centre for Human and Applied Physiology, School of Medicine, University of Wollongong, Australia.

Anna Dalecki	adalecki@uow.edu.au
Sarah P. Loughran	loughran@uow.edu.au
Adam Verrender	av138@uowmail.edu.au
Catriona A. Burdon	cburdon@uow.edu.au
Nigel A. S. Taylor	nigel_taylor@uow.edu.au
Rodney J. Croft (corresponding author)	rcroft@uow.edu.au Tel: +61 2 4221 3652 Fax: +61 2 4221 8130

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Conflict of Interest Statement

None.

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Keywords:

Radio-frequency electromagnetic fields (RF-EMF)

RF-EMF provocation

Mobile phones

Visual event-related potentials (ERPs)

P1

N1

Highlights:

- Thermal inputs to the skin were clamped for the first time to assess the impact of RF-EMF on ERPs.
- No effects of exposure were seen on P2, N2 or P3 ERP amplitudes or latencies.
- Lack of ERP effects corresponds with the lack of strong evidence for RF-EMF effects on cognition.

1. Introduction

It is well established that waking electroencephalogram (EEG) power in the alpha (8-12 Hz) band (Croft et al., 2002, D'Costa et al., 2003, Curcio et al., 2005, Regel et al., 2007, Croft et al., 2010), and sleep EEG in the sleep spindle range (Borbely et al., 1999) are both affected by radio-frequency electromagnetic field (RF-EMF) exposure. These effects persist even after RF-EMF exposure cessation for sleep EEG (Huber et al., 2002, Loughran et al., 2005, Loughran et al., 2012), and also possibly for the waking EEG (Curcio et al., 2005). However, the functional consequence(s) of this, if any, remains to be determined.

The most relevant functional consequences of EEG effects on everyday life are gross measures of performance such as response times and accuracy. Yet these have not been found to be reliably affected by RF-EMF exposure (see Regel and Achermann, 2011, Valentini et al., 2011, Barth et al., 2012 for reviews). This is unexpected, given the relationship between the EEG and cognition, if the RF-EMF effects on the EEG are real, then associated effects on cognition *would* be expected. However, it may be that the failure to find effects of RF-EMF on performance endpoints is a consequence of such exposures producing effects too small to be detectable using measures like response time or accuracy. Testing for RF-EMF-related cognitive effects using event-related potential (ERP) endpoints would address this issue. This is because ERPs are more direct measures of neuronal function that are linked to cognition, and thus they may be more sensitive for detecting possible effects of RF-EMF exposure on cognition.

Indeed, a number of studies have evaluated the effect of RF-EMF on early sensory and later cognitive ERP endpoints. There are several reports of RF-EMF effects on both early sensory and later cognitive ERPs (reviewed in Kwon and Hämäläinen, 2011). However, these all came from studies with single-blind designs and, thus, cannot be easily interpreted due to the possibility that systematic experimenter bias may have affected the results (Regel and Achermann, 2011). When taking into consideration only studies conducted under double blind conditions, early sensory ERPs have not been found to be affected by RF-EMF exposure in either visual (Hamblin et al., 2006, Kleinlogel et al., 2008, Stefanics et al., 2008) or auditory modalities (Hamblin et al., 2006, Kleinlogel et al., 2008,

Stefanics et al., 2008). Similarly, ERPs indexing later cognitive processes have not been found to be affected by RF-EMF exposure (Hamblin et al., 2006, Kleinlogel et al., 2008, Stefanics et al., 2008, Trunk et al., 2014). Despite the current lack of strong evidence supporting any effect of RF-EMF on ERPs, design limitations within the prior experiments may have reduced their sensitivity to the detection of potentially real effects, meaning that the question of RF-EMF effects has not been adequately addressed.

Limitations of prior studies include small sample sizes (limiting statistical power), incomplete counterbalancing (not accounting for treatment order effects) and the failure to include practice tasks or calibration of task difficulty level (thus increasing error variance). Studies with predominantly, or entirely, male samples may have also reduced the chance of detecting any potential real effects given that females have shown larger RF-EMF-related sleep EEG changes compared to males (Loughran et al., 2012). Furthermore, no ERP study to date has controlled thermal inputs to the body. This is despite the only known mechanism by which RF-EMF can interact with the body being a thermal one (Challis, 2005), which suggests that controlling thermal inputs is critical when testing the effects of RF-EMF exposures. That is, if the observed effects on the EEG (and thus potentially cognition) are due to small temperature increases occurring due to RF-EMF exposure, then uncontrolled, large fluctuations in ambient and, to a lesser extent, tissue temperatures may obscure any effects due to the much smaller, RF-induced thermal increases. That researchers from prior ERP studies have not attempted to control ambient thermal inputs to the body suggests the possibility that uncontrolled fluctuations in environmental temperature in prior studies may have exceeded the small temperature changes due to RF-EMF exposures. Consequently, it cannot, despite the null results in the extant literature, be concluded that previous investigations have demonstrated that RF-EMF exposure does not affect ERP indices of cognition.

In the present study, methodological improvements designed to overcome previous limitations were implemented to determine whether acute exposure to RF-EMF affects early sensory, as well as later cognitive ERPs, elicited in a visual discrimination task. Specifically, thermal feedback from the skin was clamped throughout all experimental sessions, those sessions were separated by at least 7 days to minimise the chance of carryover effects affecting the results, dose-response

effects were evaluated, the difficulty of the visual discrimination task was calibrated to individual performance levels in a separate, preliminary testing session to minimise floor and ceiling effects, and practice tasks preceded each experimental session to minimise learning effects. These improvements, in addition to the double-blind, sham-controlled and fully counterbalanced design with a gender-balanced sample were aimed at increasing the sensitivity of the present study, and thus the chance of detecting any potential effects of RF-EMF on ERPs elicited during a visual discrimination task.

2. Methods

2.1. Participants

Thirty-six participants, 18 males and 18 females, aged 18 to 52 (M = 24.4, SD = 6.3 years) participated in the study. Exclusion criteria were a history of seizures, epilepsy or serious head injury, or taking any neuroleptic medication. All participants were right handed. Participants were asked to, and reported, abstaining from alcohol for 8 hrs, caffeinated foods and beverages for 1 hr and using a mobile phone to make or receive a phone call for 2 hrs prior to their arrival at the laboratory. All participants gave informed, written consent and the study was approved by the University of Wollongong Human Research Ethics Committee (HE: 13/146).

2.2. GSM Exposure System

Simulated 920 MHz Global System for Mobile Communications (GSM) exposure was administered to the left hemisphere using an sXh920 planar exposure system (IT'IS, Zurich) (Murbach et al., 2012). The exposure system was calibrated to provide a peak spatial specific absorption rate averaged over 10g (SAR_{10g}) of 0 W/kg, 1 W/kg and 2 W/kg for the 'Sham', 'Low' and 'High' exposure conditions respectively.

To ensure double blinding was achieved, the exposure system was programmed by a researcher not involved in data collection, and it was then controlled electronically by an experimenter who was unaware of the exposure conditions programmed. Brown noise was played through speakers throughout the experiment to mask any sounds made by the exposure system and thus to ensure that participants were not aware of the exposure condition. As described in

Verrender et al. (2016), no participant correctly identified all three exposure conditions.

2.3. Study Design

The study was based on a double-blind, counterbalanced, crossover design, and involved four study visits, each at least seven days apart. The first visit was a calibration session where participants practiced the cognitive tasks to minimise practice effects in the experimental sessions and to allow the tasks to be calibrated to appropriate levels of performance for each individual separately. Study visits 2-4 involved the exposure conditions: 1) 0 W/kg, 2) 1 W/kg and 3) 2 W/kg with the order of exposure randomised and fully counterbalanced between participants and within each gender.

2.4. Procedure

Each participant was tested at the same time for all four of their study visits (with start times of either 09:00 or 13:00) to minimise circadian effects. Participants then completed a short questionnaire asking about sleep, caffeine consumption and mobile phone use, and also completed a 16-item visual analogue mood scale (Thayer, 1967).

Participants were then fitted with the physiological apparatus (described below) and seated inside a Faraday cage facing a computer screen (approximately 90 cm away) with an RF antenna (inside a box) positioned 42 mm above the left auditory canal and 115 mm away from the head. A second box containing no RF antenna was identically positioned on the right side of the head. Participants then performed a practice run of each of the cognitive tasks (described below; 2.5 min each).

Participants were also fitted with a water-perfusion suit (a cotton, long-sleeved jacket and pants containing a series of plastic tubes which covered the arms, legs, waist and torso; Cool Tubesuit, Med-Eng, Ottawa, Canada). The suit was connected to a water pump which distributed water through the tubes at a rate of 2.5 L/min for the duration of each trial. Water temperature was regulated at 34℃ using a thermostatically controlled water bath (38-litre water bath; Type VFP, Grant Instruments, Cambridge, U.K.) and was active for at least 10 minutes before testing

began. This clamping technique has been shown to successfully stabilise skin and deep-body tissue temperatures and to remove environmental influences on those temperatures (Machado-Moreira et al., 2008).

Once this set-up was complete, participants completed a 23-min baseline block during which they were not exposed to RF, while they performed an electrooculogram (EOG) calibration task (Croft and Barry, 2000) and other physiological data including resting EEG, heart rate and blood pressure were also recorded. Two (30-min) experimental blocks followed the baseline ('RF ON', where exposure was either Sham, Low or High RF according to that determined by the randomisation and counterbalancing procedure, and 'RF OFF', where exposure was always off, in that order), and these consisted of a visual discrimination and a modified Sternberg working memory task while accuracy, RT and physiological data were recorded (Figure 1). The Sternberg task forms part of Verrender et al. (2016), is not relevant to the present analyses and will not be discussed further.

2.5. Physiological Measurements

Participants were fitted with a 19 channel EEG cap (Quik-Cap, Compumedics, Neuroscan), and EEG data were recorded from 19 channels (FP1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, O2) and M2 according to the international 10/20 system. EEG data were referenced to the left mastoid (M1) and grounded midway between FPz and Fz. EOG was recorded from above (E1) and below (E3) the left eye and from the outer canthi of the left (E5) and right (E6) eyes. EEG and EOG data were recorded with an online 0.05-500 Hz analogue band-pass filter, and digitised at a rate of 2,000 Hz. All electrode impedances were below 5 kΩ at the start of the recording.

Thermistors (YSI type-EU, Yellow Springs Instruments, Yellow Springs, OH, USA) were used to measure skin temperatures from eight sites (forehead, right chest, right scapula, right upper arm, right forearm, left dorsal hand, right anterior thigh and right calf). From the latter indices, an area-weighted summation was used to derive mean skin temperature (ISO 9886:2004). All temperatures were sampled continuously (15-s intervals; 1206 Series Squirrel, Grant Instruments Ltd, Shepreth,

Cambridgeshire, UK). Mean skin temperatures, averaged over 4-min segments, from the last 4 minutes of the Baseline and minutes 0-4, (Time 1), 8-12 (Time 2), 15-19 (Time 3) and 23-27 (Time 4) of the RF ON block in each of the exposure conditions were derived for the purpose of verifying the success of the thermal clamping procedure. Deep-body temperature, blood pressure and cutaneous blood flow were also recorded however these measures are not relevant to the present study and will not be discussed further.

2.6. Visual Discrimination Task

Each trial of the visual discrimination task consisted of a cross, 'X', appearing in the centre of the computer screen for 200 ms, followed by a checked mask for 500 ms, and then a blank screen for 300 ms (see Figure 2). Participants were instructed to respond as quickly and accurately as possible with a button press whenever the arms of the cross differed in thickness from one another (Target; 50%) and not to respond when the arms of the cross were identical in thickness (Non-Target; 50%). There were 360 trials in total: 180 'easy' trials, which were always followed by 180 'difficult' trials. The difficulty levels for each participant were determined during an individual calibration session (described in Verrender et al., 2016) using signal detection theory (SDT). The advantage of this approach is that SDT separates response sensitivity (an individuals' ability to discriminate between targets and non-targets) from response bias (an individuals' tendency to respond or withhold responding), as opposed to using typical performance measures such as hit rate which confound response sensitivity with response bias. The difficulty of the perceptual task was calibrated such that individuals' performance resulted in response sensitivity, d', values of 0.8 and 0.6 for the easy and difficult versions of the task respectively. A d' value of 0 corresponds to an inability to discriminate between targets and non-targets, and larger values of d' correspond to an increasing ability to discriminate between these two stimulus types (Stanislaw and Todorov, 1999).

2.7. Data Analysis

EEG and EOG data were analysed using EDIT 4.5.1 software (Scan 4.3, Compumedics). EEG data were down-sampled to 500 Hz, re-referenced to digitally linked mastoids, EOG-corrected using the revised aligned artefact average automated ocular artefact reduction procedure (Croft and Barry, 2000), low pass filtered at 30 Hz (zero-phase shift, 24dB/octave), epoched from 100 ms pre-stimulus to 800 ms post-stimulus, and baseline corrected using the pre-stimulus interval. An automatic artefact rejection procedure then identified and rejected epochs containing EEG signals exceeding ± 100 µV in amplitude.

EEG epochs were then averaged in the time domain. The P1 (measured from O1 and O2) was defined as the most positive-going deflection 80-140 ms post-stimulus (Hamblin et al., 2006). Both the anterior and posterior N1 subcomponents (Vogel and Luck, 2000) were measured, with anterior N1 (hereafter referred to as N1a, and measured from Fz) defined as the maximal negative-going deflection 80-150 ms post-stimulus and posterior N1 (N1p, measured from O1 and O2) defined as the maximal negative-going deflection 130-200 ms post-stimulus (Berchicci et al., 2016). P2 (measured from Pz) was defined as the maximal positive deflection 180-300 ms post-stimulus (Berchicci et al., 2016). N2 to targets (N2t) and non-targets (N2n; both measured from Fz) were each defined as the maximal negative deflection 250-350 ms following targets and non-targets respectively (Berchicci et al., 2016). Finally, the P3 (measured from Pz) was defined as the most positive deflection 320-600 ms following Target stimuli (Hamblin et al., 2006). In order to maximise signal to noise ratio, early sensory ERPs (P1, N1a, and N1p) were generated by averaging responses to both target and non-target stimuli, irrespective of response accuracy. The N2t and N2n ERPs were generated by averaging correct responses to target and non-target stimuli respectively. Finally, the P2 and P3 ERPs were generated by averaging correct responses to target stimuli.

2.8. Statistical Analyses

Statistical analyses were performed with SPSS statistical package 21.0. Dependant variables were P1, N1p, N1a, N2t, N2n, P2 and P3 ERP amplitudes and latencies. The Shapiro-Wilk test indicated that the assumption of normality was violated for the following ERP amplitudes in the Sham (easy version: N2t; difficult version: P1, N1a, N2t, N2n), 1 W/kg (easy version: P1, N2n; difficult version: N2t, P3) and 2 W/kg

(easy version: P1, N1p, N1a; difficult version: P1, N1p, N1a, N2t, P3) conditions as well as the following ERP latencies in the Sham (easy version: N1p, N1a, N2t, N2n, P2; difficult version: P1, N1a, N2n), 1 W/kg (easy version: N1p; difficult version: P1) and 2 W/kg (easy version: P1, N1a, N2n, P3; difficult version: N1a, N2n) conditions, all $p < .05$. Mauchly's test indicated that sphericity could not be assumed for N1p latency values in the difficult version of the perceptual task $\chi^2(2) = 9.89$, $p < .01$. Due to these violations of normality and sphericity assumptions non-parametric statistics were performed. To first check whether ERP endpoints were affected by session order (regardless of exposure condition) a Friedman two-way ANOVA compared the rankings of ERP amplitudes and separately, latencies, across the three experimental sessions for the easy and difficult versions of the perceptual task separately. Wilcoxon signed rank tests were then performed on amplitude and latency data for each ERP and for easy and difficult conditions separately to determine whether, firstly, there was an effect of Exposure (defined as the average of the 1 W/kg and 2 W/kg conditions) compared to the Sham condition, and secondly, whether any effects were dose dependant (comparing the 1 W/kg condition against the 2 W/kg condition). We note that in the difficult version of the perceptual task, one participant did not respond and two participants were administered the incorrect difficulty level. In order to preserve complete counterbalancing, these data points were interpolated. To verify the validity of our thermal clamping procedure, a 3 (Sham, 1 W/kg, 2 W/kg) × 5 (Baseline, Time 1, Time 2, Time 3, Time 4) repeated measures ANOVA was performed on mean skin temperature values.

3. Results

3.1. Thermal clamping

To ensure that the effects of variations in the external environmental and prior physical activity did not interfere with this experiment, thermal clamping techniques were used. Mean skin temperature did not differ between the three exposure conditions (Sham, 1 W/kg and 2 W/kg) at any of the time points ($p = .33$; see Table 1). These data confirm the veracity of the thermal clamp and the stability of skin temperature throughout the experiment.

Table 1. Mean skin temperatures (℃, with standard deviation) recorded across five time points in each of the exposure conditions.

	Baseline	Time 1	Time 2	Time 3	Time 4
Sham	33.1 (0.7)	33.1 (0.6)	33.1 (0.7)	33.1 (0.7)	33.1 (0.7)
1 W/kg	33.0 (0.6)	33.0 (0.6)	33.0 (0.6)	33.0 (0.6)	33.0 (0.7)
2 W/kg	33.0 (0.6)	33.0 (0.6)	33.0 (0.6)	33.1 (0.6)	33.1 (0.6)

3.2. Order Effects

A Friedman two way ANOVA did not indicate any difference in the rankings of any ERP amplitudes or latencies across the three experimental sessions in either the easy or the difficult version of the task (all $p > .05$), with the exception of P2 amplitude. The rankings of P2 amplitudes in the easy version of the task differed across the three sessions, $\chi^2 = 7.72$, $df = 2$, N – Ties 36, $p = .02$. However, follow-up pairwise comparisons with the Wilcoxon Signed Rank test did not indicate any difference in the ranks of P2 amplitudes between sessions (all $p > .05$).

3.3. Easy version of the visual discrimination task

3.3.1. Effects of RF-EMF exposure on ERP amplitudes

P1 amplitude was reduced during Exposure (*Mdn* = 3.65 µV) compared to the Sham condition (*Mdn* = 3.79 µV) ($z = 2.34$, $p = .02$). However, this effect of Exposure did not depend on RF dose as P1 amplitude did not differ between the 1 W/kg (*Mdn* = 3.89 µV) and 2 W/kg (*Mdn* = 3.34 µV) conditions. No differences in amplitude were found when comparing the Sham and Exposure conditions for N1p, N1a, N2t, N2n, P2, or P3, nor when comparing 1 W/kg and 2 W/kg conditions for N1p, N1a, N2t, N2n, P2, or P3 (all $p > .05$) (see Table 2 and Figure 3).

3.3.2. Effects of RF-EMF exposure on ERP latencies

No differences in latency were found when comparing the Sham and Exposure conditions for P1, N1p, N1a, N2t, N2n, P2 or P3 nor when comparing the 1 W/kg and

2 W/kg conditions for P1, N1p, N1a, N2t, N2n, P2, or P3 (all $p > .05$) (see Table 2 and Figure 3).

3.4. Difficult version of the visual discrimination task

3.4.1. Effects of RF-EMF exposure on ERP amplitudes

No differences in amplitude were found when comparing Sham and Exposure conditions for P1, N1p, N1a, N2t, N2n, P2, or P3, nor when comparing 1 W/kg and 2 W/kg conditions for P1, N1p, N1a, N2t, N2n, P2, or P3 (all $p > .05$) (see Table 2 and Figure 3).

3.4.2. Effects of RF-EMF exposure on ERP latencies

N1a latency was increased during Exposure (*Mdn* = 114 ms) compared to the Sham condition (*Mdn* = 108 ms) ($z = -2.05$, $p = .04$). Again however, this did not depend on RF dose as N1a latency did not differ between the 1 W/kg (*Mdn* = 120 ms) and 2 W/kg (*Mdn* = 110 ms) conditions. No differences in latency were found when comparing Sham and Exposure conditions for P1, N1p, N2t, N2n, P2, or P3, nor when comparing 1 W/kg and 2 W/kg conditions for P1, N1p, N2t, N2n, P2, or P3 (all $p > .05$) (see Table 2 and Figure 3).

Table 2. Median (and difference between the maximum and minimum values) ERP amplitudes and latencies in the easy and difficult versions of the perceptual task with *p* values for: (*a*) Sham versus Exposure and (*b*) Low versus High comparisons (values significant at $p < .05$ are bolded).

	Easy					Difficult				
	Sham	1 W/kg	2 W/kg	*a*	*b*	Sham	1 W/kg	2 W/kg	*a*	*b*
Amplitude (μV)										
P1	3.79	3.89	3.34	**.02**	.06	3.40	4.19	2.93	.83	.28
	(7.18)	(12.74)	(10.86)			(9.30)	(8.24)	(9.09)		
N1p	-7.26	-7.16	-6.13	.48	.32	-7.23	-7.45	-7.50	.91	.89
	(14.81)	(12.81)	(21.71)			(13.48)	(13.65)	(18.11)		
N1a	-5.08	-5.11	-4.45	.89	.19	-4.37	-4.28	-4.53	.56	.62
	(9.80)	(13.40)	(12.26)			(10.10)	(16.41)	(10.67)		
N2t	-3.19	-4.11	-3.90	.91	.69	-2.98	-3.74	-3.27	.69	.39
	(21.21)	(16.84)	(19.67)			(25.48)	(17.66)	(22.04)		
N2n	-5.75	-5.39	-6.21	.93	.67	-4.97	-4.80	-5.78	.16	.22
	(20.27)	(18.65)	(20.22)			(13.84)	(17.26)	(15.50)		
P2	2.21	3.34	2.16	.10	.06	2.05	2.43	2.09	.37	.60
	(18.16)	(20.04)	(17.67)			(10.13)	(11.95)	(10.56)		
P3	8.46	8.81	8.03	.91	.18	7.51	7.28	7.84	.25	.62
	(14.34)	(21.21)	(24.13)			(24.42)	(36.75)	(19.75)		
Latency (ms)										
P1	100	100	98	.60	.31	99	98	99	.26	.66
	(50)	(46)	(46)			(53)	(36)	(44)		
N1p	152	150	153	.09	.87	152	151	152	.97	.88
	(59)	(64)	(59)			(60)	(51)	(51)		
N1a	110	117	116	.62	.59	108	120	110	**.04**	.19
	(56)	(56)	(52)			(56)	(64)	(66)		
N2t	296	294	301	.92	.25	298	300	298	.97	.16
	(94)	(90)	(94)			(94)	(90)	(94)		
N2n	300	301	299	.20	.21	307	305	304	.29	.72
	(94)	(84)	(84)			(92)	(94)	(92)		
P2	220	230	230	.50	.19	231	228	227	.15	.23
	(108)	(94)	(100)			(114)	(110)	(112)		
P3	400	415	406	.71	.73	410	409	418	.33	.27
	(232)	(252)	(198)			(226)	(206)	(216)		

3.5. Exploratory Analysis of Gender Effects

A Mann-Whitney *U* test conducted on the difference between Sham and Exposure (Sham minus Exposure) for each ERP amplitude and latency separately showed a gender difference for P1 amplitude in the easy version of the perceptual task, $U = 98$, $z = -2.03$ (not corrected for ties), $p = .04$, such that males had a smaller reduction in P1 amplitude in the Exposure condition (*Mean Rank* = 22.06; *Mdn* = -0.01 µV) compared to females (*Mean Rank* = 14.94; *Mdn* = -1.22 µV). The effect of Exposure was not found to differ between gender for any other ERP amplitude or latency in either the easy or difficult versions of the perceptual task, all $p > .05$.

4. Discussion

This experiment is the first to examine the effect of RF-EMF exposure on ERPs whilst clamping thermal feedback from the skin. This is a novel and important design feature given that the heating produced by RF-EMF exposure is the only mechanism by which RF-EMF is known to affect biological tissue (Challis, 2005). By clamping this thermal feedback, it was possible to evaluate whether the small thermal change produced by low-level RF-EMF exposure affects ERP indices of sensory and cognitive processes. In addition, the sensitivity of this experiment to detect any possible effects of RF-EMF on ERPs was maximised by a host of experimental design features incorporated to improve on methodological designs used in previous studies. The current study did not find effects of RF-EMF exposure on the majority of the ERP endpoints assessed. It was observed that during Exposure (compared to the Sham condition), P1 amplitude was reduced and anterior N1 latency was increased in the easy and difficult versions of the perceptual task, respectively. These effects, however, were not dose dependent and given the number of comparisons made, may be attributed to chance (only 2 out of 56 of the main comparisons were significant). Further, the effect of Exposure was not found to interact with gender (only 1 out of the 56 exploratory gender comparisons were significant), suggesting that differential effects between males and females do not explain the predominant lack of effects in the overall sample.

The observed reduction in P1 amplitude during Exposure compared to the Sham condition is in contrast with previous research which has failed to find an effect of RF-EMF on P1 amplitude (Hamblin et al., 2006). This discrepancy may be due to the present study being more sensitive and thus able to detect effects of RF-EMF owing to the methodological improvements incorporated (outlined in the Introduction). However, as this is the first report of an early sensory ERP being influenced by RF-EMF exposure, this observation requires replication. This is particularly important given that the difference in P1 amplitude was seen only in the easy, but not in the difficult version of the perceptual task, suggesting the possibility that this is a chance observation. If the RF-EMF exposure affected perceptual processes in the easy version of the perceptual task, one might expect the same to occur in the difficult version of the task which arguably represents a greater challenge to those processes.

With respect to dose-dependency, although the present study failed to find a statistically significant dose-response effect for P1 amplitude, P1 amplitude tended (p = .06) to be lower during the High compared to the Low RF condition. It is possible that this pattern of results reflects the presence of a threshold, where the Low (1 W/kg) dose was insufficient to affect P1 and a reduction in P1 amplitude was thus only seen at the High (2 W/kg) dose. Whether this is the case, or whether the trend toward a dose-response effect was simply due to chance, remains to be resolved as the minimal exposure dose required to elicit EEG and potential ERP and cognition changes have not yet been experimentally determined.

In the present study, it was also observed that N1 latency was increased during Exposure compared to the Sham condition. However, not only did we not observe a dose-response effect, but the N1 latency was lower (not statistically significantly) in the High RF condition compared to Low RF. This suggests that the increase in N1 latency observed during Exposure was driven by the Low RF condition. Indeed, the N1 latency in the High condition (110 ms) was similar to Sham (108 ms), raising the possibility that the observation of the increased N1 latency during Exposure may be due to chance. Given that this is the first study to assess the effect of RF-EMF on N1 latency, this result requires replication.

Overall, these observations imply that even with strong methodology, RF-related alterations were not seen in most early sensory or later cognitive ERPs. It is possible that RF-related alterations in the early sensory (P1) (Klimesch, 2011) and preparatory motor (N1a) (Vogel and Luck, 2000) processes observed in the current study are only detectible with the strong design and methods that were employed. However, it is notable that no later cognitive ERP amplitudes were found to be affected (either by RF-EMF exposure itself or via downstream effects of the early alterations to processes reflected by P1 amplitude and N1a latency). Nor were the response times or accuracy of button presses in response to target stimuli affected by RF-EMF exposure in these participants (results pertaining to performance measures are reported in Verrender et al., 2016). We note that, given that the easy version of the perceptual task always preceded the difficult version, this may have influenced reaction time results (Belopolsky et al., 2010, Lamy and Kristjánsson, 2013). This lack of effects on later cognitive ERP endpoints, as well as performance measures (Verrender et al., 2016), corresponds to the existing double-blind studies in the RF-EMF ERP literature which did not yield effects of RF-EMF on ERP indices of sensory and cognitive processes (Hamblin et al., 2006, Kleinlogel et al., 2008, Stefanics et al., 2008, Trunk et al., 2014). This suggests that if real, the RF-related differences in early ERPs observed in the present study are very small and nullified by compensatory processes, and thereby would not be sufficient to result in effects on later cognitive ERP components or measures of performance. However, the lack of dose-dependence, the lack of patterning of significant effects over difficulty or ERP component, and given that only two ERP endpoints differed statistically strongly suggests that these were chance observations.

It should be noted that the RF-EMF exposure in the present study was a simulated GSM signal, delivered via planar antenna (Murbach et al., 2012). This planar antenna delivers a relatively homogenous SAR distribution to brain structures in the exposed hemisphere (Murbach et al., 2012). By using two SAR doses: 2 W/kg to represent the maximal SAR permitted to be emitted by a mobile phone handset (ICNIRP, 1998) (thus theoretically maximising the chances of detecting any possible effect), and 1 W/kg to represent a ‘low’ RF-EMF dose (thus allowing for the testing of any possible dose-response effects), our use of the planar exposure system allowed for testing the hypothesis that these simulated GSM exposures, delivered

homogenously to the entire exposed hemisphere, affected central nervous system function. We note that, in contrast to the homogenous SAR distribution produced by the planar antenna used in the present study, exposures from individual mobile phones are far more localised, such that SARs in brain regions more distant from the mobile phone are markedly smaller than those more proximal to the phone (Boutry et al., 2008, Loughran et al., 2008). Therefore, given the lack of effects on central nervous system function under conditions where the maximal SAR is delivered to the entire hemisphere, it is unlikely that a markedly smaller, localised SAR exposure, such as that which might be present during mobile phone use, would affect the processes assessed in the present study.

5. Conclusion

Thermal feedback from skin temperature was successfully clamped in this experiment. Under these conditions, and in an experiment with a strong design, the majority of ERP amplitudes and latencies did not show effects of RF-EMF exposure. Only two ERP indices were found to be statistically different between the RF-EMF and Sham condition. Specifically, P1 amplitude was reduced and N1 latency was increased during RF-EMF Exposure, as compared to the Sham condition. That only two ERP indices out of 56 comparisons differed during Exposure compared to Sham suggests that these observations are likely due to chance. However, even if they turned out to be real, the failure to observe effects of RF-EMF exposure on response time and accuracy in these participants in this visual discrimination task (Verrender et al., 2016) suggests that the small ERP effects observed here do not meaningfully affect performance.

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Figure Legends

Figure 1. Schematic illustrating an experimental session.

Figure 2. An example of: (a) a non-target; (b) an easy target (which resulted in mean response times of 359 ms, SD = 39 ms); (c) a difficult target (which resulted in mean response times of 373 ms, SD = 43 ms); and (d) the checked mask that appears in between stimulus presentations.

Figure 3. P1, N1p, N1a, N2t, N2n, P2 and P3 ERPs elicited under each of Sham, 1 W/kg and 2 W/kg exposure conditions in the easy (left) and difficult (right) versions of the perceptual task. The electrode sites from which ERPs were derived are shown in brackets.