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Neuropsychological sequelae of digital mobile phone exposure in humans

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Abstract

The effect of electromagnetic fields from digital mobile phones (DMP) on cognitive functioning is an area receiving increased attention. This study compares the performance of 120 volunteers on 8 neuropsychological tests during real or sham exposure to a DMP set to maximum permissible radiofrequency power output. When results were adjusted for known covariates (gender, age, or education), several alterations at significance levels of $p < 0.05$ were obtained. Of these, simple and choice reaction times (CRT) showed strong evidence of impairment. Further, performance on the Trail Making Task (TMT) improved, supporting the hypothesis that DMP radiofrequency emissions improve the speed of processing of information held in working memory.

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Keywords: Cognition; Electromagnetic field; Reaction times; Working memory

1. Introduction

Concern has developed regarding the possible hazardous effects of exposure to radiofrequency electromagnetic radiation (RFR) emitted from mobile phones. One area that has received increased attention over recent years is the possible effect of electromagnetic fields on neurobehavioural and cognitive functioning.

Digital mobile phones (DMP) operate at various different frequency bands, ranging from 850 to 1900 MHz. The most widely used cellular network, the Global System for Mobile Communication (GSM), operates at 900 and 1800 MHz, with peak power levels of 2 and 1 W, respectively (Smythe & Costall, 2003). The DMP frequency band of interest to this study for its common use is the 900 MHz frequency band, in which information is transmitted in bursts of power at a basic repetition frequency of 217 Hz and a 1:8 duty cycle for GSM systems (Linde & Mild, 1997). The average power of the 900 MHz DMP is thus 0.25 W. Due to close proximity, the head and brain absorb part of the RFR energy emitted by the mobile phone (Schönborn, Burkhardt, & Kuster, 1998). The amount of RFR absorbed by biological tissue is referred to as specific absorption rate (SAR), which is defined in Watts per kilogram (W/kg) (Royal Society of Canada, 1999). The National Council of Radiation Protection (NCRP) for general public exposure recommended that the spatial peak SAR should be 1.6 W/kg, as averaged over 1 g of tissue (NCRP, 1993). This limit represents the most stringent US national guidelines for the exposure of humans to RFR energy in the frequency band 800–900 MHz, as measured at the time of introduction of portable cellular phones in 1984. The peak spatial SAR limits recommended by the Australian National Standards (ARPANSA, 2002) are 2 W/kg for the head and torso, and 4 W/kg for the limbs.

As the nature of directly measuring internal electric fields is invasive, SAR assessments in humans have typically been achieved by using a “phantom” model of the human head. Based on such modelling, the SAR from a 900 MHz cellular phone to the head has been found to range from 0.16 to 0.69 W/kg, and to the brain from 0.06 to 0.41 W/kg (Gandhi, 1995). Such SAR ranges are dependent on the distance of head to antenna separation (Kuster & Balzano, 1992). As such, the possible effect of the absorbed RFR energy on the brain and cognitive functioning has become a topic of interest.

Past research investigating the effect of RFR emitted by DMP on human cognitive functioning, have produced mixed results. Preece et al. (1999) reported improved cognitive func-

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tioning with exposure to 915 MHz RFR (to simulated analogue and digital phones formed from a 1/4 wave antenna). Specifically, subjects performed faster (that is, RT decreased) on a CRT task, when they were exposed to DMP RFR. This improvement however, was only significant for simulated analogue phone exposure (whose output power was 1 W, as opposed to 0.125 W for the simulated digital phone). No changes in performance were observed for the word, number or picture recall tasks, or for the spatial memory tests. Koivisto, Revonsuo et al. (2000) also observed a significant improvement in RT during exposure to 902 MHz (pulse modulated at 217 Hz) RFR, but on simple RT and vigilance tasks. Additionally, the cognitive time needed in a mental arithmetic task decreased during field exposure. Examination of the effect of RFR on memory load by Koivisto, Krause, Revonsuo, Laine, and Hämäläinen (2000) also showed improved RT when memory load was three items, but no effects on RT were observed with lower memory loads. Similarly, Edelstyn and Oldershaw (2002) observed improved performance on the forward digit span, backwards spatial span, and serial subtraction cognitive tasks, following 30 min exposure to 900 MHz DMP RFR. A facilitating effect on attentional functions was also reported by Lee et al. (2001), who found that DMP users performed better on the Trail Making Task (TMT) than non-DMP users. Improvement in short-term memory with DMP exposure was also observed by Smythe and Costall (2003) who found fewer errors in the recall of word placement in a spatial configuration with exposure to 1800 MHz DMP RFR. This finding however was only evident for males, with the errors generated by females being largely unaffected across exposure conditions.

Impaired, or no changes in cognitive functioning with DMP RFR exposure have also been reported. Maier, Greter, and Maier (2004) reported impaired cognitive performance on an auditory discrimination task following the exposure of 902 MHz RFR (pulse modulated at 217 Hz). Haarala et al. (2003, 2005) failed to find any effect of RFR emitted by a 902 MHz mobile phone on the RTs or accuracy of adults and children, respectively, across a set of cognitive tasks. Subsequently, the researchers argued that either DMP RFR has no immediate effect on human cognitive functioning, or that any such effects are so small that they are only occasionally observed. The results of Haarala et al. (2003, 2005) were supported by Besset, Espa, Dauvilliers, Billiard, and de Seze (2005), who found that daily exposure (2 h daily for 5 days over 4 weeks) to 900 MHz RFR (pulse modulated at 217 Hz) had no effect on cognitive function, specifically, to information processing speed, attention capacity, memory function, and executive function.

It is evident from the literature that the effects of DMP RFR on cognitive functioning are still unclear. The aim of this experiment was to further examine the cognitive effects of DMP emissions, using well-validated neuropsychological tests, and a substantially larger sample size (120 subjects). Based on previous literature, it was predicted that any changes in cognitive performance with DMP RFR would likely be illustrated by improved RT (that is, decreased RT) for RT tasks (Koivisto, Revonsuo et al., 2000; Preece et al., 1999), and also for more complex working memory tasks (Koivisto, Krause et al. 2000).

2. Methods

2.1. Participants

One hundred and twenty healthy volunteers participated in the study and provided informed consent to do so. The sample comprised 58 males and 62 females, with age ranging from 18 to 70 years ($M = 33$ years, S.D. = 13). The average number of years education was 14.7 years (S.D. = 2.69). The study was approved by the Swinburne University Human Research Ethics Committee.

2.2. Experimental design

A double-blind crossover design was employed in order to ensure that both the subject and the experimenter were blind to the exposure condition. The study comprised two testing sessions per participant, which were separated by approximately 1 week. One testing session involved exposure to a 'real field' condition, and the other testing session involved exposure to a 'sham field' condition. The two testing conditions were balanced for order. In the 'real field' condition, the DMP was set at full power for the entire exposure period (which would normally only happen when speaking into the phone in weak signal areas). In the 'sham field' condition, the DMP was set on standby. During each session, subjects began by completing a battery of eight psychological tests during which there was no DMP exposure. On completion of the test battery, a non-metallic helmet, modified to create a headset that the DMP could be clipped to, was placed on the subject's head for the first 30 min of exposure (either real or sham field condition). The 30 min exposure duration was measured via a standard clock with second hand. The DMP rested against the subject's left ear with the antenna 1.5 ± 0.5 cm from the head. The psychological tests were then re-administered to the subjects during the continuation of exposure (30 min after exposure had begun). Each testing session required approximately 60 min. In order to minimise practice effects, alternate forms of the psychological tests were used on the four occasions each subject was tested, and the tests were counterbalanced for order.

A genuine GSM DMP (Nokia 6110) was used for the exposure period in all testing sessions (for both real and sham exposures). For the real exposures, computer software provided by the manufacturer was used to set the DMP at 0.25 W mean power. A specific frequency channel was reserved with a telecommunications carrier for the local base station.

2.3. Double-blinding

A just-perceptible buzzing sound was emitted by the DMP when it was set on full power, despite the removal of the speaker. To eradicate the possibility of subjects being aware of this, the DMP was covered with soundproofing material. The phone also became warm after being on full power for an extended period of time (approximately 1 h). To prevent subjects from detecting whether the DMP was emitting or on standby, a 5 mm thick piece of foam was placed between the phone and the subject's head. This also aided in the consistent positioning of the phone handset in relation to the face. As some computer screen displays exhibit movement when a DMP is nearby, due to electromagnetic interference, a non-reactive screen was selected for use in presenting task stimuli.

Normally a DMP gives an audible cue when the batteries run low. The following measures were taken to prevent either the experimenter or the subject hearing this cue: (a) the largest size batteries were used, enabling full power transmission for 4 h; (b) the DMP was turned off immediately at the end of a session; and (c) the DMP was completely recharged between sessions.

A pilot test was also conducted to determine whether subjects detected any difference between the real and sham conditions with the DMP placed in the headset ($n = 19$). Of the sample, five subjects believed they could detect a difference. Of the five subjects, two subjects determined the condition correctly and three were incorrect. Thus, correct detection was actually worse than chance, and the result likely reflected random probability.

2.4. Exposure system

The power output was measured at 0.23 W in independent tests conducted by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). This was slightly below the expected value of 0.25 W, most likely due to losses in the data cable used to connect the laptop to the phone. For sham exposures the DMP was in standby mode.

2.5. *Neuropsychological testing*

The eight cognitive tests employed in the study are summarised in Table 1 and have been discussed in an earlier publication (Keetley, Wood, Stough, & Sadafi, 2001). The first five tests (AVLT, DS, DSST, SCT, and TMT) involved paper-and-pencil tests. The final three tests (RT, CRT, and IT) were administered as computer-run tasks (thinkFAST). Median RTs were recorded from the RT, CRT, and IT tasks as the median offers a more accurate appraisal of central tendency than mean RT, and is also less influenced by outliers. In total, there were 18 main experimental variables that were assessed. These included 13 scores from the primary tests and an additional 5 derived from the formulae below:

AVLT Learning Rate (LR) = AVLT (Trial 5 − Trial 1).
AVLT Retroactive Interference (RI) = AVLT (Trial 5 − Trial 7).
AVLT Forgetting Rate (FR) = AVLT (Trial 8 − Trial 7).
AVLT Retrieval Efficiency (RE) = AVLT (Trial 9 − Trial 8).
TMT Difference (TMT D) = TMT A − TMT B.

3. Results

The sample was intended as a cross-section of the population, including a mix of gender, age, and level of education. The tests employed have been previously documented to be sensitive to at least one of these variables as shown in the last column of Table 1. The effects of these covariates on statistical power for each test were also used to determine which particular ones to include.

In order to determine whether "real field" exposure had a significant effect on neuropsychological performance in comparison to "sham field" exposure, 2 (real field, sham field) × 2 (pre-exposure, exposure) repeated-measures Analysis of Covariance (ANCOVA) were calculated for each cognitive measure. Each repeated-measures ANCOVA calculated the change in performance between "pre-exposure" and "exposure" for each condition (real and sham), and then determined whether

Table 1
List of eight tasks used in study

Test	Task	Score	No. of comparisons	Skills tested	Covariates
Rey's Audio-Visual Learning Test (AVLT)	Verbal recall of a list of 15 disyllabic words. Repeated 8 times, trial 7 (T7) given after an 'interference' list (T6), T8 given 0.5 h after T7. T9 used only for subjects scoring < 13 in T8	No. correct (out of 15)	8: AVLT1, 7, 8, 9, AVLT LR, RI, FR, RE	Immediate recall (T1); verbal learning (T1–T5); long-term memory (T8)	Gender (Vakil & Blachstein, 1997)
Digital Span (DS)	Verbal recall of a number, either in the same order (DS forwards) or reverse (DS backwards) as the digits read out	No. correct (out of 10)	2: DS fwd, DS bck	Efficiency of attention (DS forwards); working memory (DS backwards)	Age (Lezak, 1995), education
Digital Symbol Substitution Test (DSST)	9 symbols paired with numbers 1–9. Symbols to be substituted for 100 numbers in fixed period	No. correct in 90 s	1: DSST	Motor persistence; sustained attention; response speed; visuo-motor coordination	Age (Lezak, 1995; Salthouse, 1985; Tun, Wingfield, & Lindfield, 1997), education
Speed of Comprehension Test (SCT)	100 simple statements requiring true/false response in fixed period	No. correct in 2 min	1: SCT	Language comprehension; rapid decision making; visual scan; psycho-motor speed	Age, education
Trail Making Task (TMT)	A: draw a continuous line connecting 25 circled digits; B: as A, but digits and letters alternate	Time (s) for correct completion	3: TMT A, B, D	Visual-conceptual; visual motor tracking	Age (Stanton, 1984)
Reaction Time (RT)	Press ↓ key as soon as possible after stimulus presented on computer screen	Response latency (ms)	1: RT median	Response latency	Age (Bosman, 1993; Salthouse, 1985), education
Choice Reaction Time (CRT)	4 keys represent 4 quadrants on computer screen: press key corresponding to quadrant turning yellow; however, the displayed 'moat' has two colours: the precise key to be pressed depends on the colour of the 'moat'	Response latency (ms)	1: CRT median	Stimulus perception; discrimination of response choice; motoric response	Age (Coleston, 1989), education
Inspection Time (IT)	A target stimulus is followed after a very short time by a mask. Identify which of two limbs of a 'pi' figure is longer and press appropriate key	Minimum duration (ms) for 80% accuracy	1: IT median	Speed of intake of information	Age (White, 1993), education (Stough, Brebner, Nettlebeck, & Cooper, 1996)

Factors (covariates) known to affect outcome are listed in the final column.

Table 2
Means and S.D.s for each cognitive measure, before and during DMP exposure, for the 'real field' and 'sham field' conditions

Measure	*N*	Real field				Sham field				Significance (*p*)	Performance
		Pre-exposure		Exposure		Pre-exposure		Exposure			
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.		
AVLT trial 1	120	7.83	1.89	6.73	2.06	7.89	1.98	6.85	2.49	NS	
AVLT LR	120	5.15	1.95	5.80	2.12	5.05	2.08	5.86	2.49	NS	
AVLT trial 7	117	11.50	2.86	10.20	3.65	11.40	2.73	10.69	3.41	0.043	Impairment
AVLT trial 8	111	11.31	3.12	9.01	4.13	11.41	2.58	9.41	4.08	NS	
AVLT trial 9	46	12.15	2.05	9.87	3.46	12.43	2.08	10.39	3.58	NS	
AVLT RI	117	1.48	1.67	2.33	2.24	1.55	1.66	2.03	1.94	NS	
AVLT FR	111	1.77	2.01	3.60	2.78	1.64	1.70	3.42	2.65	NS	
AVLT RE	46	3.59	2.40	3.59	2.93	3.00	1.91	4.22	3.38	0.005	Impairment
DS fwd	120	9.61	2.35	9.51	2.18	9.60	2.18	9.53	2.10	NS	
DS bck	120	8.33	2.62	8.47	2.64	8.33	2.81	8.68	2.72	NS	
DSST	120	66.71	12.60	67.61	12.68	65.88	12.68	67.34	13.20	NS	
SCT	115	70.26	19.65	75.34	20.98	69.86	18.59	74.69	21.30	NS	
TMT A	119	27.17	9.04	25.28	8.29	27.38	10.52	25.33	9.71	0.019	Impairment
TMT B	120	63.34	30.90	59.96	25.99	61.68	26.40	59.61	25.78	0.020	Improvement
TMT difference	120	36.15	27.04	34.79	22.21	34.62	21.21	34.34	21.86	0.004	Improvement
RT median	109	268.21	34.76	271.20	45.62	268.33	33.99	267.39	38.20	0.005	Impairment
CRT median	110	656.69	160.46	626.95	139.98	658.32	171.58	623.49	156.22	0.011	Impairment
IT median	109	75.45	21.51	70.29	20.62	76.31	20.52	73.95	30.03	NS	

Significance levels for ANCOVAs with adjustments for covariates are as given in Table 1. Where changes are significant at $p < 0.05$, effect on performance is indicated.

the change observed for the sham condition was significantly different from the change observed for the real field condition.

Table 2 shows the means and standard deviations for each cognitive measure, in each condition, both before and during exposure. The means and standard deviations also represent the actual changes in performance that occurred as a result of exposure to the DMP emissions, before the covariates were taken into account. The statistical values in Table 2 however are the results from the ANCOVAs. None of these variables achieved significance values of $p < 0.05$ if covariates were not taken into account. For the significant results, Table 2 also states whether exposure to the DMP improved or impaired cognitive performance for that task. Impairment in cognitive performance with DMP RFR was indicated when the difference in performance between pre-exposure and exposure of the real field condition was significantly poorer than the difference in performance between pre-exposure and exposure in the sham field condition. In contrast, improvement in cognitive performance with DMP RFR was indicated when the difference in performance between pre-exposure and exposure of the real field condition was better than that of the sham condition. It should be noted that differences in sample size are the result of incorrect task completion, different inclusion criteria or unavailability of software.

Given that it was predicted that cognitive changes related to the DMP emissions would reduce RTs in RT tasks, and in working memory tasks, changes at a Type 1 error rate of less than 0.05/2 were regarded as evidence to reject H_0. Factor analysis of all the cognitive variables in the study revealed two independent cognitive factors relating to working memory and information processing. A Bonferroni correction for all cognitive variables was therefore not regarded to be appropriate.

4. Discussion

The findings of impaired RTs (RT and CRT) with DMP emissions, rejects the hypothesis that they would improve. Aside from the fact that the literature is extremely mixed, findings of an improvement in RT with DMP exposure has not been a stable observation. For example, where Koivisto, Revonsuo et al. (2000) observed a significant reduction in simple RT, no change in RT was observed in CRT. The opposite pattern was observed by Preece et al. (1999), in which RT was significantly reduced for CRT, but not for simple RT. These findings suggest that the hypothesis may have been based on weak evidence. The findings also emphasise the argument of Haarala et al. (2003), that any such effects of DMP RFR on cognitive functioning may be small and thus only occasionally observed.

Methodological differences between the present study and those of Preece et al. (1999), Koivisto, Revonsuo et al. (2000), and Koivisto, Krause et al. (2000) may have also contributed to differing results. Unlike the present study, there was no washout period between the two exposure conditions in the study of Koivisto, Krause et al. (2000), and very short washout periods of approximately 24 and 48 h respectively in the studies of Koivisto, Revonsuo, et al. (2000) and Preece, et al. For the instances where a subject received the "field on" condition first, the effects of exposure may have carried over into the second testing condition. Additionally, practice effects on the tasks may have masked treatment effects. A more obvious difference between studies is that of sample size. Koivisto, Revonsuo et al. (2000) and Koivisto, Krause et al. (2000) tested 48 subjects, and Preece et al. tested a sample size of 36. The present study increased the statistical power considerably by expanding the sample size to 120 subjects. The larger sample size allowed the present study to elucidate the more specific effects of DMP exposure on cognition. Further, neither Preece et al., nor Koivisto, Revonsuo et al. (2000) and Koivisto, Krause et al. (2000) excluded covariates that have been documented to be sensitive to variables such as gender, age, and level of education. Also, unlike the present study, Koivisto, Revonsuo et al. (2000) and Koivisto, Krause et al. (2000) used a single-blind design which may have made their research vulnerable to errors due to inter-individual variation in cognitive performance, and exposed it to possible experimenter bias.

As shown in Table 2, it was also observed that RT improved for the TMTB and TMT difference (a specific test of working memory), thus supporting the hypothesis that exposure to DMP RFR emissions would improve RTs for working memory tasks. No changes were observed for DS backwards, which also tests working memory, but here accuracy rather than speed is measured. The non-significant finding for DS backwards is in agreement with the error rate measurements of a previous study (Koivisto, Krause et al. 2000). Improved RT for the TMT working memory tasks supports the finding of Koivisto, Krause et al. (2000), who suggested that RFR emitted by DMP may be affecting higher level cognitive functions which require higher levels of attention and working memory. Whilst the finding of improved RT for the TMT is accepted with confidence, the finding should still be approached with some caution given the absence of a known mechanism of biological interaction at these exposure levels.

Interestingly, Huber et al. (2002, 2005) observed an increase in relative regional cerebral blood flow (rCBF) in the dorsolateral prefrontal cortex ipsilateral to 30 min pulse modulated RFR from a 900 MHz DMP. Such a finding implicates that blood flow changes caused by RFR may underlie some of the cognitive changes that have been observed with DMP RFR, given that the prefrontal cortex plays a major role in working memory. It has also been proposed that a temperature rise in the cerebral cortex as a result of DMP RFR may be related to changes in cognitive performance with exposure to DMPs (Preece et al., 1999). Modelling research however, suggests otherwise with exposure to 915 MHz from an average emitted power of 0.25 W being found to only generate a brain temperature rise of 0.11 °C for a realistic head model (Van Leeuwen et al., 1999). This degree of temperature change was suggested to be far too small to have any lasting effects (Van Leeuwen et al., 1999) thus implying that effects of DMP emissions on cognitive performance are likely to be non-thermal related. Future confirmatory investigations may choose to employ techniques such as functional Magnetic Resonance Imaging (fMRI) to further elucidate the neurophysiological changes associated with GSM emissions. Examination of the anatomical sites involved in the cognitive processes that are influenced by DMP exposure is also an area for further investigation.

The results of this study provide statistical evidence of a cognitive difference in performance between the real and sham field DMP exposure conditions. The negative effects of DMP exposure on RT performance indicate that the more basic functions were adversely affected by exposure. In contrast, the improved RT for the TMT working memory task suggests that DMP exposure has a positive effect on tasks requiring higher level cortical functioning, such as working memory. The implications of this study can only be directed towards the effects of short-term exposure of DMP RFR on cognition. Further longitudinal research is required to determine the effects that long-term use of DMPs (years) may have on health and cognition.

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