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11 **Does the Use of Mobile Phones Affect Human Short-Term**  
12 **Memory or Attention?**  
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21 SUMMARY

22 The effect of acute exposure to low-level radio frequency electromagnetic fields (REF) generated by  
23 mobile phones on short-term memory and attention was assessed in two experiments. Most of the  
24 tests manipulated task difficulty or what might be termed cognitive load. This manipulation is  
25 important since previous studies have argued that exposure to mobile phones might affect cognitive  
26 functions only under conditions which tax the cognitive system. All participants were exposed to REF  
27 (half were exposed to GSM—Global System for Mobile Communication—signals and the other half  
28 were exposed to unmodulated signals) in one testing session, while in a separate session participants  
29 were exposed to sham signals. To investigate potential lateralised effects, the mobile phone was  
30 positioned on the left side of the head for half of the participants and on the right side for the other  
31 half. No significant effect of exposure to REF was detected in any of the six tasks used in either the  
32 low or high cognitive load conditions. This study used much larger sample sizes than is typical for this  
33 type of research and REF exposure was administered under double-blind conditions. Overall, the  
34 results indicate that acute exposure to REFs emitted by mobile phones do not have a strong impact on  
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36 The widespread use of mobile phones has raised concerns about the possible effects that  
37 low-level radio frequency electromagnetic fields (REF) emitted by these devices might  
38 have on human health. In the recent years, the increasing number of studies examining the  
39 possible effects of REF exposure on neuronal activity and cognitive functions has produced  
40 results that are often inconsistent or difficult to compare (because of the differences in  
41 experimental methodologies). Several studies found that REF exposure may cause changes  
42 in the regional cerebral blood flow (e.g. Aalto, Haarala, Bruck, Sipila, Hamalainen, &  
43 Rinnie, 2006; [Huber et al., 2005<sup>Q1</sup>](#)) and in the electro-neurophysiological activity (Freude,  
44 Ullsperger, Eggert, & Ruppe, 2000; Hamblin, Wood, Croft, & Stough, 2004; Krause et al.,  
45 2000a, 2000b). However, other studies did not find any significant changes on neural  
46 activities (e.g. Röschke and Mann, 1997) or failed to replicate previous positive results  
47 (Krause et al., 2003). More studies reported that acute exposure improved cognitive  
48 performance on attention and short-term memory tasks (e.g. Curcio, Ferrara, De Gennaro,  
49 Cristiani, D’Inzeo, & Bertini, 2004; Edelstyn & Oldershaw, 2002; Koivisto, Krause,  
50 Revonsuo, Laine, & Hämaläinen, 2000; Koivisto et al., 2000; Lee, Lam, Yee, & Chan,  
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2003; Preece et al., 1999; Smythe & Costall, 2003), others claimed to have found both improved and reduced performance (Keetley, Wood, Spong, & Stough, 2006). However, in Keetley et al. study, significant outcomes were only detected after adding a series of constant covariates, like age and education, to each within-subjects factorial ANOVA aimed to test the effect of the phone on-off variable on cognitive tasks, otherwise no statistical test reached significance. Furthermore, it is to be noted that, since each participant was assessed both with the mobile phone on and with the mobile phone off, adding covariates measured before the administration of the test (i.e. which values do not change during the course of the experiment), cannot affect the outcome of an interaction involving purely within-subjects factors (Norusis, 1985). Therefore, it is not clear how adding constant covariates to a fully within-subject factorial ANOVA the *F* ratios of the interactions, that in Keetley et al. (2006) intended to assess the impact of the REF exposure on cognitive performance, could be affected. Finally, a few others have failed to detect any significant effect on cognitive performance (Russo et al., 2006; [Haarala et al., 2003<sup>Q2</sup>](#), 2004). Possible reasons for the contradictory results on the effects of mobile phones may include, for example, the use of very small sample sizes (often fewer than 20 participants) and REF exposure not being administered under double-blind conditions. This is not overly surprising given that a number of studies have reported effects as being significant without applying any correction for multiple statistical tests. For example, if the Bonferroni approach (which keeps the probability of Type I errors at 0.05) had been applied (Koivisto et al., 2000; Preece et al., 1999), the null hypothesis about the effect of exposure to mobile phone would have been rejected in only one study and for only one task (i.e. Koivisto et al., 2000; vigilance task). Indeed, our group recently reported the results of a double-blind study (Russo et al., 2006) where a large sample of adult volunteers ( $n = 168$ ) performed a series of attentional tasks that previous studies (e.g. Curcio et al., 2004; Koivisto et al., 2000; Preece et al., 1999) had claimed were affected by REF exposure. No significant effect of REF exposure on performance was found in any of the tasks. There is, nevertheless, a range of different cognitive functions and tasks not tapped in the studies mentioned above, thus it remains possible that some aspect of cognitive functioning might be affected by acute exposure to mobile phones. The present study provides a further assessment of the effects of exposure to REF generated by GSM and CW mobile phones on a wider variety of memory and attention tasks than have been used in previous research. We also manipulated cognitive load in the current study, since previous studies have claimed that any improvement in cognitive function due to REF exposure might only occur under conditions that impose a relatively high cognitive load (Koivisto, Krause, et al., 2000).

In order to provide sufficient statistical power to allow us to confidently reject the null hypothesis, we tested two samples of 160 participants, with double-blinded REF exposure. Making the conservative assumption that REF exposure has a small effect on cognitive performance (i.e. effect size,  $d = 0.3$ ) then an experiment with 160 participants would have a statistical power greater than 0.95 to reject a false null hypothesis about the effect of REF exposure. Also, testing under double-blind conditions seems important since many effects reported under single blind conditions have not stood up to the test of replication under double-blind REF exposure ([Haarala et al., 2003<sup>Q3</sup>](#), 2004; Russo et al., 2006).

Finally, to assess if there is any differential effect of GSM modulated vs. CW unmodulated signals, half of the participants were exposed to an 888 MHz CW signal and the remaining half were exposed to an 888 MHz GSM signal. Furthermore, half of the participants were tested with the mobile phone positioned on their left ear, and the remaining half had the phone on the right ear, so that we could test any potential laterality

effects (see also Reference Eliyahu, Luria, Hareuveny, Margalioth, Nachshon, & Gad, 2006).

In Experiment 1, 160 volunteers performed a vigilance task (see also References Koivisto et al., 2000; Russo et al., 2006), and a *n*-back<sup>Q4</sup> task (see also References Koivisto, Krause, et al., 2000; Haarala et al., 2004). In Experiment 2, 168 volunteers performed a Stroop task, a Stenberg task (i.e. a short-term memory task) and a visual search task, for each task included various levels of difficulty so that different levels of cognitive load could be assessed. All participants were tested in two different sessions: one with REF exposure and the other with sham exposure, under double-blind conditions.

Q4

## EXPERIMENT 1

In [Experiment<sup>Q5</sup> 1](#), we used some of the tasks that previous studies showed were affected by REF exposure: a *n*-back task (Koivisto, Krause, et al., 2000) and a vigilance task (Koivisto et al., 2000). The *n*-back task (Koivisto, Krause, et al., 2000) is a short-term memory task in which participants are shown a long sequence of items, and for each item presented they have to decide whether or not the current stimulus was shown earlier in the sequence (e.g. 2 or 3 positions back). Koivisto, Krause, et al. (2000) reported that reaction times (RTs) in the 3-back task condition (with letters used as stimuli) were faster when participants were exposed to GSM signals, but no significant effect was detected when participants performed a 0-back, 1-back and 2-back versions of the task (note that, in a replication study, Haarala et al. (2004) failed to find any effect of REF exposure on the 3-back task). In the present study, we included a 2-back and a 3-back task, where either lists of letters or list of unfamiliar faces were presented. This last type of stimuli was included to maximise the possibility of detecting lateralised effects of REF exposure (e.g. Kim et al., 1999; Rhodes, 1985). Face processing and recognition appear to be carried out more efficiently by the right hemisphere. Therefore, if exposure to REF does affect face processing, it should be detected—or should be stronger—when the phone is positioned on the right.

Q5

In Experiment 1, participants also performed a vigilance task (Koivisto et al., 2000) in which they were shown either a single letter or a string of six letters—thus providing two levels of cognitive load—and had to decide whether or not one of three designated target letters was presented.

## Methods

### *Participants*

One hundred and sixty volunteers, mostly university students (116 women, 44 men; average age: 22.2 years), were tested in two different sessions, 1 week apart. In one session participants were exposed to REF: a random half of the participants with GSM modulated signal and the other half with CW unmodulated signal. In the other session there was no exposure. In that case the power, either in the GSM or CW conditions, was actually diverted to an internal load of the phone. The order of REF/sham exposure was counterbalanced across participants. Both participants and experimenters were blind to the REF/sham exposure conditions (i.e. experimenters and participants did not know whether or not the phone was on or off). Dials at the back of the phones allowed to pre-select codes for REF emitting and sham conditions. Neither the experimenters nor the participants knew the relation between codes and conditions.

### Equipment

A mobile phone was fixed on a 'cage/cap' that was mounted on the head of each participant so that the telephone microphone was close to the mouth and the antenna was touching or very close to the head, above and slightly behind the ear.

The mobile phone could emit GSM modulated and CW unmodulated signals at 888 MHz as well as a sham signal. The level of specific energy absorption rate (SAR) in the present study was the same for both CW and GSM signals (with SAR within the International Commission on Non-Ionising Radiation Protection guidelines). The average SAR in both modes was 1.4 W/kg ( $\pm 30\%$ ). For the GSM mode the peak SAR was 11.2 W/kg (CW does not have a peak). The SAR in the no exposure condition was less than 0.002 W/kg. The above features correspond to the approved exposure system made for the Mobile Telecommunication and Health Research Programme in the UK.

([http://www.mthr.org.uk/meetings/nov\\_2002/summaries/human\\_exposure.htm](http://www.mthr.org.uk/meetings/nov_2002/summaries/human_exposure.htm))

In all the tasks, stimuli were presented on a computer screen.

### Procedure

Participants were asked not to use any mobile telephone for at least 1 hour before each session. At the beginning of each session, once the phone set was mounted and activated, participants had to complete a subsection of the Raven's matrices for a maximum of 5 minutes, to allow the mobile phone to 'warm up'. Then the following tasks were completed:

*n-back letter task.* Participants were presented with a long sequence of letters and for each one they had to decide whether or not it was the same as the one presented  $n$  letters earlier in the sequence. They pressed either a 'yes' or 'no' key on the computer keyboard as soon as they could. Each participant performed a 2-back task and a 3-back task, in which each letter was compared with the one presented respectively 2 and 3 positions back. In each version of the task, participants were presented with a sequence of 120 letters. Target letters (i.e. letters that were the same as the one presented  $n$  positions back) occurred 36 times. Each letter was shown until a response was given and the following one appeared after 1 second. Each task was preceded by a practice session.

*n-back faces task.* This task was identical to the  $n$ -back task with letters, with the only difference being that unfamiliar faces were used as targets instead of letters.

*Vigilance task.* Displays showing either a single letter or a string of six letters were presented for 200 milliseconds and participants had to press the spacebar any time they saw one of the target letters (target letters being L, M and Y), independently of whether the target was presented as single letter or within a string. The inter-stimulus interval randomly varied from 500 to 3000 milliseconds. Each participant was presented with a series of 360 trials (180 single-letters and 180 letter-strings, randomly intermixed) of which 72 (20%) were target trials.

For each task, RTs were the critical measures of performance. Participants were always given, in the order, one of the two  $n$ -back tasks (either with letters or faces), the vigilance task, then the remaining  $n$ -back tasks. The order in which each type of  $n$ -back task (either

Table 1. RT (in milliseconds) in Experiment 1 as a function of the position of the phone (Left vs. Right) and REF exposure (On vs. Off)

Task	Phone position	On	Off	<i>p</i> -value
2BL	Left	923	896	>.58
	Right	815	823	>.81
3BL	Left	1123	1192	>.30
	Right	876	906	>.50
3BF	Left	857	855	>.93
	Right	835	856	>.64
3BF	Left	1017	1052	>.55
	Right	930	909	>.61
VT single	Left	304	305	>.70
	Right	302	303	>.74
VT string	Left	508	503	>.69
	Right	504	496	>.38

The *p*-values refer to the test of the On vs. Off variable. Since the type of phone variable never interacted significantly with the REF variable the data are collapsed over the type of phone used. The alpha level used for each test was 0.0042 (i.e. 0.05 divided by the number of tests performed).

2BL, two-back task letter; 3BL, 3-back task letter; 2BF, 2-back task faces; 3BF, 3-back task faces; VT single, vigilance task single letter; VT strings, vigilance task strings of letters.

2-back or 3-back, either with letters or faces) was administered was counterbalanced across participants.

In each session participants were exposed to REF for about 45 minutes.

## Results

Table 1 shows the average of the median RTs, calculated on correct responses, for each task. Statistical analyses (mixed factorial ANOVAs) were performed on the log transformed median RT performance of each participant.

### *n*-back letter task

The factors considered in the analysis were the following: Type of signal (CW vs. GSM), REF exposure (On vs. Off), Phone's position (Left vs. Right), Cognitive Load: High vs. Low), Type of Trial (Target vs. Non-target). As expected, there was a significant difference between the low and high load tasks [ $F(1, 156) = 48.7, p < .01$ ]; RTs for the 2-back task (864 milliseconds) were faster than RTs for the 3-back task (1024 milliseconds). The difference between target trials (895 milliseconds) and non-target trials (993 milliseconds) was also significant [ $F(1, 156) = 14.6, p < .01$ ]. This difference was more pronounced in the 2-back task than in the 3-back task [ $F(1, 156) = 25.5, p < .01$ ]. However, RTs were unaffected by REF exposure [ $F(1, 156) < 1$ ], and none of the interactions involving the REF factors were significant [ $F_s(1, 156) < 3.15, p > .07$ ], apart from a four way REF exposure by Phone position by Cognitive Load by Type of signal interaction [ $F(1, 156) = 7.44, p < .01$ ]. Factorial ANOVAs on high (3-back) and low (2-back) cognitive load trials were computed separately in order to follow-up this significant interaction. The REF exposure factor was not significant and no interaction involving this factor approached significance in either the 2-back task nor in the 3-back task conditions [ $F_s(1, 156) < 1.43, p > .10$ ].

*n-back faces task*

The factors considered were the same as those analysed in the *n-back* task with letters. Participants were once again faster to respond in the 2-back task (851 milliseconds) than in the 3-back task (957 milliseconds), [ $F(1, 156) = 69.2, p < 0.01$ ]. They were also faster with target faces (886 milliseconds) compared to non-targets (942 milliseconds) [ $F(1, 156) = 13.6, p < .01$ ]. This difference was more pronounced in the 2-back task than in the 3-back task [ $F(1, 156) = 57.7, p < .01$ ]. Once again, there was no significant main effect of REF exposure [ $F(1, 156) < 1$ ], nor any significant interaction involving this factor [ $F(1, 156) < 2.43, p > .10$ ], apart from a four-way REF exposure by Phone Position by Cognitive Load by Type of trial interaction [ $F(1, 156) = 5.0, p < .05$ ]. Factorial ANOVAs at the each of the level of the Cognitive load factor were carried out. Neither the REF exposure factor was significant nor any interaction involving this factor approached significance (with Bonferroni's correction), both in the 3-back condition [ $F_s < 1$ ] and in the 2-back condition [ $F_s(1, 158) < 4.52, p > .035$ ].

*Analyses on accuracy.* For each type of *n-back* task accuracy in the performance measured as  $A'$  scores (Donaldson, 1992) was calculated for each participant (a score of 0.5 represents chance while a score of 1 represents perfect discrimination). There was only a significant effect of the cognitive load factor [ $F(1, 156) = 171, p < .01$ ], ( $A' = 0.85$  in 2-back trials and  $A' = 0.93$  in 3-back trials). Similar results were found when faces were used as targets: participants were more accurate in the 2-back ( $A' = 0.80$ ) than in the 3-back ( $A' = 0.90$ ) condition [ $F(1, 156) = 208, p < .01$ ].

*Vigilance task*

In the mixed factorial ANOVAs the following factors were considered: Type of signal (CW vs. GSM), Phone's position (Left vs. Right), Cognitive Load (Single Letter vs. String), REF exposure (On vs. Off). There was a significant main effect of Cognitive Load [ $F(1, 156) = 1294.4, p < .01$ ], with shorter RTs for single letters (303 milliseconds) than for strings of letters (502 milliseconds). REF exposure did not have a significant effect on performance and this factor did not significantly interact with any other variable [ $F_s(1, 156) < 1.74, p > .10$ ].

*Analyses on accuracy.* The proportion of missed items and the proportion of false alarms were smaller in the 'single' condition than in the 'string' condition (missed items: 0.03 and 0.18, [ $F(1, 156) = 307, p < .01$ ]; false alarms: 0.02 and 0.04, [ $F(1, 156) = 52.1, p < 0.01$ ]).

**Discussion**

In all three tasks (*n-back* letter task, *n-back* faces task and vigilance task), the only significant effects were those related to the cognitive load of the tasks: RTs in the 2-back tasks were faster than in the 3-back tasks. Similarly, in the vigilance task target detection was faster and more accurate in single letter trials than trials comprising strings of letters. However, the most important result is that we did not find any effect of REF exposure on performance (both RTs and accuracy). Moreover, no modulation of the influence of REF exposure on performance as a function of task difficulty was detected. This contrasts with previous results (Koivisto, Krause, et al., 2000) where GSM exposure speeded up RTs in the 3-back task, but only when targets were presented. We did not find such an effect, neither when letters were presented, nor when faces were presented. Given the size of our

sample (160 subjects) the present experiment had considerably more statistical power than Koivisto, Krause, et al. (2000) study where 48 subjects were tested. Moreover, unlike Koivisto and collaborators' single blinded administration of REF exposure we used a double-blind procedure. This, as shown by Haarala et al. (2003<sup>Q6</sup>, 2004), is an important factor in the assessment of the effect of REF on cognitive tasks.

Q6

## EXPERIMENT 2

Experiment 2 included a short-term memory task (Sternberg task) and two attentional tasks (a Stroop paradigm and a visual search task), which have not been used previously to test the effects of REF exposure on human behaviour (though see Reference Haarala et al. (2003)<sup>Q7</sup> where a different version of our Stroop task is described). The Sternberg task (Sternberg, 1966) is a short-term memory task where observers are asked to attend to series of stimuli and then decide whether or not, in each series, a probe stimulus was presented. Typically, the shortest the list, the fastest the RTs. However, RTs do not depend on whether or not the probe is in the list.

Q7

Visual search paradigms (e.g. Treisman and Sato, 1990) have been largely used to investigate the role of attention on visual features binding. In our study, a conjunction search was performed, where a target with a particular combination of features has to be searched for (e.g. a red T) within a set of distractors that share one of the target features (e.g. red Xs and green Ts). Typically, the larger the number of distractors, the slower the RTs, and search is slower for 'target-absent' sets than for 'target-present' sets.

Stroop paradigms are often used to study suppression of automatic responses (Stroop 1935). In our study participants were tested in a version of the Stroop task in which strings of digits were shown and the number of digits in each string was incongruent with the digit represented in the string. Participants had to say how many digits were shown in each string. This was compared to a control condition where strings of Xs were presented. Haarala et al. (2003)<sup>Q8</sup> found that there were no effects of REF exposure on RTs and accuracy of a Stroop task. However, in their study colour words were used as stimuli.

Q8

## Methods

### *Participants*

One hundred and sixty-eight participants, mostly university students (112 female and 52 male; average age: 23 years, range 18–42, SD = 5), completed all tasks twice, in two different sessions (on average, 7 days apart). The REF exposure procedure was the same as in Experiment 1. Both participants and experimenters were blind to the on–off exposure condition. None of the people tested in this experiment took part in Experiment 1.

### *Procedure*

The preliminary procedure was the same as in Experiment 1. Then the Sternberg task, the Visual search and the Stroop task were performed in a counterbalanced order. During each session, each participant was exposed to REFs for about 40 minutes. The procedure used for each of the three experiments was as follows.

*Stroop task.* On each trial, either a string of digits or a string of Xs was presented at the centre of the screen. The number of items of each string varied from 1 to 5. Digit strings



were repetitions of the same number, which could be any from 1 to 5 (e.g. '5555', or '33333'). However, the number of items of each digit string was always different from the number printed in that string (e.g. it could never be '22' or '4444', etc.). The task was to name, as quickly and as accurately as possible, the number of items on each string. The stimulus display lasted until a verbal response was given and then the following stimulus display appeared after 1 second. Each participant was presented with one block of 120 trials, preceded by instructions and a practice session. Strings of digits and string of Xs were randomly presented with the same frequency.

*Visual search task.* Participants were randomly shown displays of 5, 15 or 30 coloured letters (Ts and Xs) pseudo-randomly positioned on the display. All displays showed green Xs, brown Xs and brown Ts (called distractors). A green T—the target—and only one, might be presented and the task was to decide, as quickly as possible, whether, on each display, the target was present or not. The response was given by pressing a 'yes' or a 'no' key. The target was randomly shown on half of the trials. A display with a fixation cross-preceded each letter display for 500 milliseconds. Letter displays appeared for 3 seconds or until a response key was pressed. Then, the following trials started after 500 milliseconds. Each participant was presented with a total of 384 trials in three blocks, where all conditions were randomly intermixed. A practice block of 20 trials preceded the experimental blocks.

*Sternberg task.* Each participant was presented with 68 sequences of pictures. The pictures were black and white drawn (objects and animals) and were presented (for 1 second) in sequences of 4 or 6. Every sequence was followed by a display showing either sum or subtraction (1 digit numbers only, e.g.  $3 + 4$ ) and participants had to say the solution to a microphone. The display disappeared when the response was given. After that, a single probe picture was presented, and participants had to decide whether or not that picture was shown in the last presented sequence. The answer was given by pressing a 'yes' or 'no' key. After an interval of 4 seconds a new sequence was shown. Positive probe pictures were randomly presented half of times. All conditions (i.e. positive and negative probe, and 4 and 6 picture sequence) were randomly intermixed.

## Results

Table 2 shows the average of the median RTs according to each condition, for correct responses, for each experiment. Mixed factorial ANOVAs were performed on the log transformed median RTs.

Note that in the data analysis of each experiment, for different reasons, not all 168 participants' data were included and, therefore, degrees of freedom differ from task to task.

### *Stroop task*

A mixed factorial ANOVA was performed using the following factors: Type of signal (CW vs. GSM), REF exposure (On vs. Off), Phone's position (Left vs. Right) and Stroop Condition (Control vs. Incongruent). As expected, participants were faster to respond to rows of Xs (669 milliseconds, Control condition) than rows of digits (699 milliseconds, Incongruent condition; [ $F(1, 156) = 288.1, p < 0.01$ ]). The main effect of REF exposure was not significant [ $F < 1$ ], but the interaction between REF exposure and Stroop Condition was significant [ $F(1, 156) = 6.78, p < .02$ ]. With strings of Xs, participants

Table 2. RT (in milliseconds) in Experiment 2 as a function of the position of the phone (Left vs. Right) and REF exposure (On vs. Off)

Task	Phone position	On	Off	<i>p</i> -value
Stroop-XXX	Left	663	671	>.23
	Right	668	674	>.33
Stroop-Dig.	Left	694	697	>.64
	Right	704	701	>.70
VS-5	Left	696	690	>.55
	Right	695	687	>.42
VS-15	Left	917	913	>.76
	Right	900	901	>.93
VS-30	Left	1257	1245	>.59
	Right	1237	1217	>.33
Sternberg-4	Left	1154	1161	>.79
	Right	1136	1076	<.015
Sternberg-6	Left	1194	1201	>.78
	Right	1165	1130	>.15

The *p*-values refer to the test of the On vs. Off variable. Since the type of phone variable never interacted significantly with the REF the data are collapsed over the type of phone used. The alpha level used for each test was 0.0033 (i.e. 0.05 divided by the number of tests performed).

Stroop-XXX, Stroop task control; Stroop-Dig, Stroop task Digits; VS-5, VS-15, VS-30, Visual search task with either 5, 15 or 30 items in the display; Sternberg-4, Sternberg-6, Sternberg task with either 4- or 6-item list.

mean RT was 665 milliseconds when exposed to REF signals and 673 milliseconds in the sham condition [ $F(1, 156) = 10.74, p < .01$ ], while when participants had to respond to rows of digits performance was comparable in the REF exposure and sham condition (699 milliseconds).

*Analyses on accuracy.* Participants were more accurate in the Control condition (97.6% correct) than in the Incongruent condition (96.8%; [ $F(1, 156) = 8.6, p < 0.01$ ]). Accuracy was not affected by REF exposure [ $F < 1$ ]. However, there was a significant interaction between Stroop Condition and REF exposure [ $F(1, 156) = 7.78, p < 0.01$ ]. When presented with strings of Xs, participants were correct in 97.4% of the trials when exposed to REF signals and 97.9% in the sham condition [ $F(1, 156) = 1.91, p > .10$ ]. When participants had to respond to rows of digits accuracy was 97.3% in the REF exposure condition and 96.3% in the sham condition [ $F(1, 156) = 6.57, p < .02$ ]. No other statistically significant effects were found.

#### Visual search task

The factors considered in the statistical analysis were: Type of signal (CW vs. GSM), REF exposure (On vs. Off), Phone's position (Left vs. Right), Type of Display (Target vs. Non-target) and Cognitive Load (5, 15 and 30 items). Participants were faster to respond when the target was present (772 milliseconds) than when absent (1120 milliseconds; [ $F(1, 155) = 1313, p < .01$ ]). There was also a significant main effect of Cognitive Load [ $F(2, 310) = 2367, p < .01$ ] with RTs increasing as display size increased (5 items: 692 milliseconds; 15 items: 908 milliseconds; 30 items: 1239 milliseconds). The interaction between the two factors was also significant [ $F(2, 310) = 676, p < .01$ ], with the effect of display size being greater when the target was absent. However, REF exposure

did not have any significant effect on the visual search task and did not interact significantly with any other factor [ $F_s < 2.49$ ,  $p > .08$ ].

*Analyses on accuracy.* Participants were more accurate when a target was not presented than when the target was shown (97.7% and 93.2% respectively; [ $F(1, 155) = 92.3$ ,  $p < .01$ ], and they were more accurate when a smaller number of items was presented (5 items: 97.4%; 15 items: 96.5%; 30 items: 92.6%; [ $F(2, 310) = 59.9$ ,  $p < .01$ ]. The interaction between Cognitive Load and Type of Display was also significant [ $F(2, 310) = 51.2$ ,  $p < .01$ ] with the difference in accuracy between Target and Non-target trials increasing as the number of items shown increased. No other main effect or interaction was significant.

### *Sternberg task*

The factors considered in the statistical analysis were: Type of signal (CW vs. GSM), REF exposure (On vs. Off), Phone's position (Left vs. Right), Sequence Load (4 items vs. 6 items) and Probe (Positive vs. Negative). RTs were faster in the 4-item condition (1132 milliseconds) than in the 6-item condition (1173 milliseconds); [ $F(1, 156) = 34.6$ ,  $p < .01$ ]. There was no significant main effect of REF exposure [ $F(1, 156) = 1.96$ ,  $p > .10$ ], and no interaction involving this factor was significant [ $F(1, 156) < 3.17$ ,  $p > .07$ ].

*Analyses on accuracy.* Accuracy was affected by the length of the list: 87.8% of correct responses with 4 items and 84.7% with 6 items [ $F(1, 157) = 47.4$ ,  $p < .01$ ], and participants were more accurate with negative probes (87.3%) than with positive probes (85.1%) [ $F(1, 157) = 4.76$ ,  $p < .05$ ]. A significant three-way interaction including REF exposure, Phone's position and Probe was detected [ $F(1, 157) = 3.96$ ,  $p < 0.05$ ]. Follow-up analyses were carried out at each level of the phone position factor. None of these analyses showed any significant outcomes [ $F_s < 3.15$ ,  $p > .07$ ].

## **Discussion**

In Experiment 2 participants performed three tasks. A Stroop task, a visual search task and short-term memory task. Task difficulty affected performance in all tests (both in terms of RTs and accuracy). However, none of the tasks was affected by REF exposure, and this effect was not modulated by task difficulty (apart from the Stroop tasks). These results are consistent with those obtained in Experiment 1, where it was shown that neither short-term memory nor sustained attention were affected by REF exposure.

It was found that RTs were significantly faster with REF exposure in the control condition of the Stroop task, with no difference being found on the incongruent trials. This pattern of results indicates that we should be cautious about interpreting this as a genuine REF exposure effect. First, this effect occurred when cognitive load was minimal, so that an REF effect occurred under conditions where it should be least likely to be observed. Moreover, when accuracy data were analysed the opposite effect was found with accuracy being significantly higher in the incongruent condition when REF exposure was present. This result is more in line with previous research which claims that any improvement in cognitive function due to REF exposure should occur under conditions that impose a relatively high cognitive load (Koivisto, Krause, et al., 2000). However, the contradictory results (i.e. faster RTs in the control condition with REF exposure without any significant

effect on accuracy coupled with greater accuracy in the incongruent condition associated with REF exposure but without any significant effect on RTs) make this result very difficult to interpret. Given that this pattern of results was not observed in any of the other tasks we used in the present study, nor in any of the tasks described in our previous research (Russo et al., 2006), we consider that the above outcomes in the Stroop task are likely to reflect Type I statistical errors, even though we are aware that they might reflect a genuine effect.

## GENERAL DISCUSSION

In two experiments, we investigated the possible effects of acute exposure to REF generated by a standard mobile phone on human cognition. Across six different tasks, participants' performance was not significantly affected by REF exposure. This was true whether participants were exposed to GSM or CW signals and whether the phone was positioned on the left or right side of the head. These results are consistent with other recent reports that REF exposure does not seem to affect cognitive performance in human participants (Haarala et al., 2003<sup>Q9</sup>, 2004; Russo et al., 2006). The current results go beyond previous reports, however, in using a wider range of tasks and also showing that REF did not affect cognitive functions under high degrees of cognitive load. Moreover, our study had a much higher degree of statistical power than previous reports (greater than 95% power to reject a false null hypothesis) and therefore provides more secure evidence for the absence of any major effects of acute exposure to mobile phone handsets on human cognitive functioning.

The study of the effect of exposure to REF on behaviour and health parameters is a controversial area of science, which generates significant public interest and concern. Research to date suggests that any effect on biological systems induced by the use of mobile phones is unlikely to be due to thermal effects. Numerous studies including the present one also seem to indicate that the non-thermal effects of mobile phones also do not affect cognitive functioning, at least in the short term. This is not surprising as there seems to be no viable theoretical basis to predict non-thermal effects of microwave fields on biological systems (e.g. Maier et al., 2004<sup>Q10</sup>). Within this theoretical vacuum, it is of concern that research reports demonstrating an effect of REF fields generated by mobile phones on behavioural or on health parameters have not been subsequently replicated when more sophisticated and precise methodologies have been used (e.g. Repacholi, 1997; Krause et al., 2000<sup>Q11</sup>, 2003; Utteridge, Gebiski, Finnie, Vernon-Roberts, & Kuchel, 2002).

In summary, the results we obtained do not preclude the possibility that exposure to REF fields generated by mobile phones may affect other aspects of cognitive functions that were not measured by the tasks we used, or that long term use of mobile phones may affect cognitive functions. While acknowledging the need for further research, the current results do indicate that acute exposure to REFs from mobile phone handsets are unlikely to have strong effects on cognitive functions.

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expressed in the publication are those of the authors and not necessarily those of the funders.

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