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Effects of Radiofrequency Radiation Emitted By Cellular Telephones on the Cognitive Functions of Humans

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The present study examined the effects of exposure to Electromagnetic Radiation emitted by a standard GSM phone at 890 MHz on human cognitive functions. This study attempted to establish a connection between the exposure of a specific area of the brain and the cognitive functions associated with that area. A total of 36 healthy right-handed male subjects performed four distinct cognitive tasks: spatial item recognition, verbal item recognition, and two spatial compatibility tasks. Tasks were chosen according to the brain side they are assumed to activate. All subjects performed the tasks under three exposure conditions: right side, left side, and sham exposure. The phones were controlled by a base station simulator and operated at their full power. We have recorded the reaction times (RTs) and accuracy of the responses. The experiments consisted of two sections, of 1 h each, with a 5 min break in between. The tasks and the exposure regimes were counterbalanced. The results indicated that the exposure of the left side of the brain slows down the left-hand response time, in the second—later—part of the experiment. This effect was apparent in three of the four tasks, and was highly significant in only one of the tests. The exposure intensity and its duration exceeded the common exposure of cellular phone users. Bioelectromagnetics 27:119–126, 2006. © 2005 Wiley-Liss, Inc.

Key words: cognitive function ability; left hemisphere; right hemisphere; GSM

INTRODUCTION

The dramatic increase in cellular phones usage raises the question of the existence of possible biological effects of radio-frequency electromagnetic radiation (RFR) [Stewart, 2000]. Although the effects of the utilized frequencies (~0.9 and ~1.8 GHz) have been studied before, two new developments in cellular technology warrant our attention:

1. Never before have so many people (especially children) been exposed to RFR, at non-negligible intensities with such proximity to the head (although within permitted levels according to IRPA/ICNIRP, 1998, FCC, 1996, CENLEC, 2001 exposure standards).
2. Most modern cellular systems operate in a pulsating mode in which the data is accumulated and transmitted in short pulses. Such modulated RFR at low average power has been reported to have effects on the central nervous system [Bawin et al., 1975; Blackman et al., 1979, 1980].

Several recent studies on the effects of exposure to RFR from cellular phones report that exposure to 900 MHz has an identifiable effect on electroencephalogram (EEG). Klaus and Joachim [1996] found changes in the EEG pattern of sleeping subjects during the exposure to GSM RFR. The radiation source in the said report had an 8 W output and the power density at the head was estimated to be 0.05 mW/cm^2. The subjects were exposed for 8 h from one side only. Further studies [Wagner et al., 1998] tried, but failed, to replicate the results of this study.

A study by Krause et al. [2000] tested the effects of GSM cellular phone on the EEG during an auditory

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memory test. A standard GSM phone (at 902 MHz) was attached to the right posterior temporal region of the head under two exposure conditions: on or off. Their findings indicated that EMF decreased the theta band activity only during their memory retrieval task, and increased the alpha band activity. However, a replication study by Krause et al. [2004] did not confirm these findings.

An epidemiological study by Oftedal et al. [2000] in Sweden and Norway looked for symptoms such as headaches, feelings of discomfort or warmth behind/around the ear in GSM users and NMT users. Their results indicated that mobile phone users experienced a variety of symptoms either during or shortly after a phone call. A study by Koivisto et al. [2001] compared subjective symptoms or sensations, such as head aches, dizziness, fatigue, itching, tingling of the skin, redness and sensations of warmth on the skin in two groups of 48 subjects, who were exposed to RFR for 30–60 min. Their results did not reveal significant differences between the exposure and non-exposure conditions.

The effects of RFR on cognitive functions were examined in several studies. Preece et al. [1999] conducted tests on a variety of short-term and long-term memory tasks, and reaction time (RT) tests. The subjects were exposed to RFR at 915 MHz (1 and 0.25 W powers). They reported a reduction in RT, with the shortest response time when the subjects were exposed to 915 MHz at 1 W.

Similar tests were conducted by Koivisto et al. [2000a]: 12 different RT tests were conducted under the exposure to 902 MHz at 0.25 W. In three of the tests, a reduction in the RT was observed. Another study by Koivisto et al. [2000b] examined the effects on the working memory, and revealed a reduction in RT under exposure to 902 MHz at 0.25 W.

In two replications and an extension study done by Haarala et al. 2003, 2004, 64 subjects in two different laboratories in Finland and Sweden performed double-blind cognitive and short-term memory tasks. The phone was attached to the left side of the head. No statistically significant differences were found between laboratories, and they did not replicate the Koivisto et al. [2000a,b] results.

The Present Study

The goal of the present study was to examine whether RFR can affect cognitive functions. The subjects were asked to perform four different tasks while being exposed to different RFR condition. The tasks chosen were those that are known to have high hemisphere specificity, i.e., they activate mostly one side of the brain (see Smith and Joindes, 1999 for a review article). The four tasks were a verbal item recognition task (left side), a spatial item recognition task (right side), and two spatial compatibility tasks (the left compatible stimuli activate the right side, while the right compatible stimuli activate the left side).

Subjects were exposed to RFR alternatively to the left side, to the right side and sham exposed. To the best of our knowledge this is the first study that compares effects of exposure to the two head sides within the same task. This allows us to test the hypothesis of the present work, that performance of specific tasks is affected by one side exposures only.

MATERIALS AND METHODS

Thirty-six healthy right-handed male subjects were chosen. The mean age was 24 years, ranging from 19 to 27. The experiment was approved by the Ben-Gurion University Medical School Ethical Committee (Beer–Sheva, Israel). The subjects gave an informed written consent. The subjects completed a questionnaire concerning intakes of tea, coffee, alcohol and the amount of sleep they had prior to the experiment. The participants reported adequate sleep in the night prior to the experiment, and they did not drink excessively or use CNS-affecting drugs.

Cognitive Tasks

The subjects were requested to perform four different tasks. The examined parameters were the response time (RTs) and the percentage of erroneous responses made by the subjects. In all tasks, subjects were instructed to react to the stimuli presented on a computer screen by pressing given buttons (''/''—using the index finger of their right hand or ''z''—using the index finger of their left hand) on the computer keyboard as quickly and accurately as possible.

As differentiation between hemispheres was one of the objects of the present study, the tasks chosen were those for which hemisphere differentiation is well established.

The tasks were coded as follows:

Spatial item recognition task—"FACE". In this task, three targets ''faces'' were presented sequentially, for 650 ms each, in three random locations on the screen, chosen out of eight possible locations. After a 3.5 s interval, another face appeared in a random location. The subject had to decide whether the last face matched the location of any of the three target faces. They were instructed to press the ''/'' when there was a match, or ''z'' when there was no match. This task is known to activate a region in the right premotor cortex [Smith et al., 1998; Smith and Jonides, 1999]. Figure 1 illustrates this experiment.

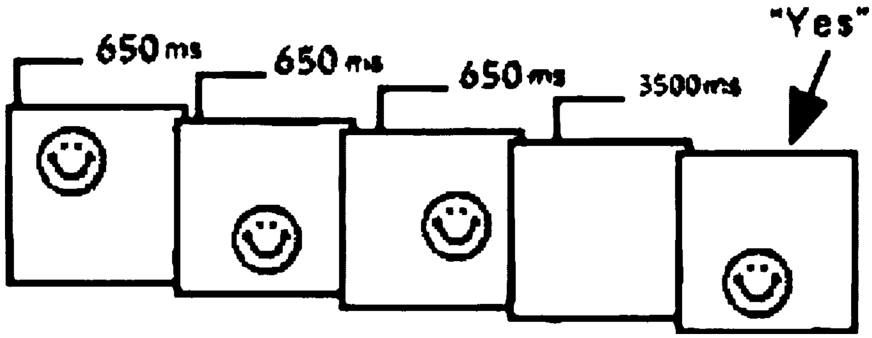

Fig. 1. "FACE"—spatial item recognition task—the subjects task is to decide whether the probe face is in the same location as any of the target faces.

Verbal item recognition task—"LETTER". In this task, a small set of target uppercase letters was presented simultaneously for 0.5 s, followed by a single lowercase probe letter after a delay interval of 3 s. The subject had to decide whether the probe matched any of the target letters by pressing "/" when there was a match or "z" when there was no match. This task is known to activate the left posterior parietal cortex, three frontal sites, and the left supplementary motor and premotor areas [Smith et al., 1998; Smith and Jonides, 1999]. Figure 2 illustrates this experiment.

Spatial compatibility—"SPAT". In this task, a letter was presented either on the left or on the right side of a fixation letter. The subject had to activate the left or the right hand according to the side of the letter. This task is assumed to activate the right posterior parietal cortex, when the letter is in the right side of the fixation letter, and the left posterior parietal cortex when the letter is on the left side of the fixation point [Peri and Zeki, 2000]. Figure 3 illustrates this experiment.

Spatial compatibility—"SIMON". In this task, the subject had to respond to stimuli that appeared either on the left or the right side of a fixation letter. When the symbols Π or θ appeared, the subject had to respond with his left or right hand, respectively. Previous studies indicate that [Simon and Rudell, 1967; Simon, 1990] when the side of the stimulus' presentation matches the responding hand (the compatible condition), responses were faster than when there is no match between the side of the stimulus and the responding hand (the incompatible condition). This is called the Simon effect [Simon and Rudell, 1967; Simon, 1990]. Figure 4 illustrates this experiment.

The test was divided into two sessions: a first 1 h series of tasks, a 5 min break, and then another hour of tasks. Before the first hour the subjects performed a 5 min training session of the four tasks employed in the experiment in order to minimize training effects.

All subjects performed all four tasks under either, left, right, or sham exposure conditions. This resulted in 12 sub-sessions per subject. Each subject performed a total of 1614 trials in all four experiments.

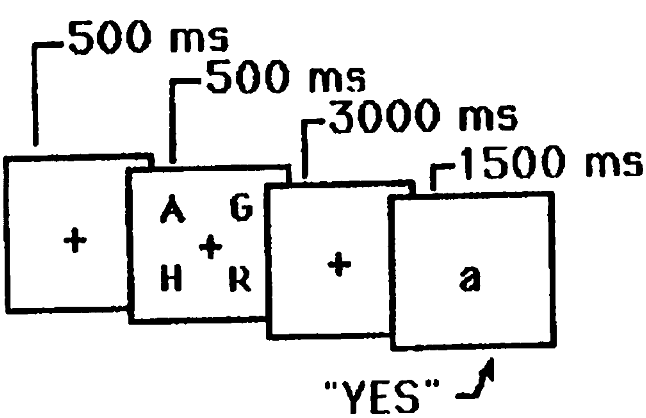

Fig. 2. "LETTER"—verbal item recognition task—the subjects task is to decide whether the probe matches any of the target letters.

RF Exposure

Each subject had two standard Nokia^{TM} 5110 GSM cellular phones attached to his head by a specially designed non-conductive frame. The phones were placed on both sides of the head, as shown in Figure 5.

We controlled the cellular phones power by using an HP GSM test system model E6392B. The phones were operated with test SIM cards (Wavetek). This

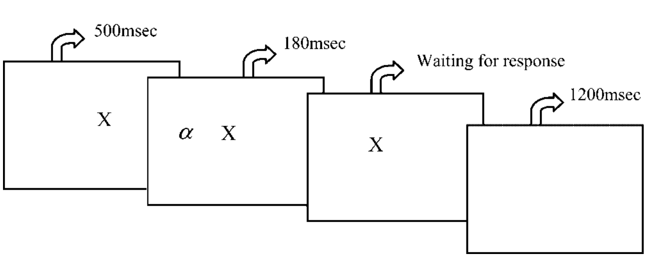

Fig. 3. "SPAT"—spatial compatibility—the subject has to activate the left or the right hand according to the side of the letter.

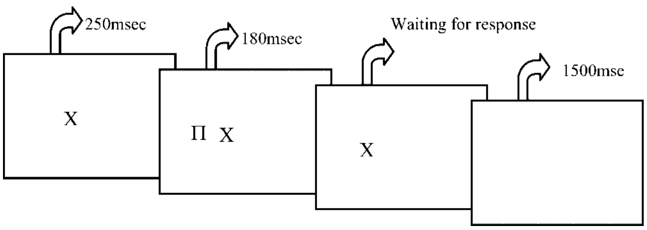

Fig. 4. “SIMON”—spatial compatibility—when the symbols Π and θ appeared, the subject had to press his left or right hand, respectively.

system maintained the phones at either no transmission or full power transmission (890.2 MHz, 33 dBm = 2 W peak power, using the typical GSM pulse duration of 577 μs and duty cycle of 1/8, yielding 0.25 W average power). The communication between the phones and the test system was wireless, at an extremely small output power (0.01 mW peak output power, as compared to the 2 W peak output of the phones); thus, we consider it negligible. During the experiment, the phones were battery operated. The phones were mounted on the subject’s heads before the first task and dismounted after the final task.

At the end of the experiments, the subjects were requested to assess whether and when the phones operated. They were unable to distinguish between exposure/sham-exposure situations, and between the sides of the exposures.

All tasks utilized the standard laboratory PC-based software (Micro Experimental Laboratory 2.0^{TM}) and experiments were presented on 14 inch screens. The subjects used standard 104-key computer keyboards.

In case of an erroneous response, the computer emitted a 400 ms beep at 500 Hz. The exposure regime and the order of the tasks were counterbalanced across subjects according to a balanced Latin square design. Each subject served as his own control, namely, his performance without exposure was compared to his own performance under exposure (a repeated measures design). The RF exposure regime was single-blinded, i.e., the experiment manager was aware of the exposure mode, while the subjects were not, since the phones were silent all the time. An opaque partition was placed between the experiment manager and the subjects during the experiment.

Fig. 5. A subject during the experiment, with the phone frame attached. [The color figure for this article is available online at www.interscience.wiley.com.]

RESULTS

In each task, trials with response times longer than 3 s and shorter than 100 ms were screened out. Only trials in which the response was correct were included in the response time analyses. In the present work, Greenhouse–Geisser correction was applied to the df’s, and corrected P-values were reported for all factors (when df > 2). No speed-accuracy trade-off was observed in any of the tasks.

A repeated measures analysis of variance (ANOVA) including Exposure condition (right hemisphere, left hemisphere, and sham exposure), Session (part one or part two), and Responding Hand (right or left) as within dependent variables on the average RT in each condition was performed.

Results for the FACE Task

The triple interaction between exposure, session and side was significant ($F(2, 62) = 3.40$, $P = .037$) see Figure 6a and b. For most exposure conditions, we observed a reduction in the response/RT from the first to the second session (with either sham exposure, or exposure to the right side of the brain). This result is probably due to training (see Fig. 6a). However, in the left hemisphere exposure condition, a reversed pattern was observed when subjects responded with their left hand: the RT in the second part of the experiment was significantly prolonged relative to the first part, from 907 to 931 ms ($F(1, 32) = 6.30$, $P = .01$) and this pattern was significantly different from the sham exposure and right side exposure averaged together ($F(1, 32) = 5.17$, $P = .02$) see Figure 6b.

There was also a significant main effect of Responding Hand, ($F(1,32) = 13.3$, $P < .001$) indicating that RT was 48 ms (from 864 to 912 ms) faster for the right hand responses (recall that all subjects were right handed).

Results for the LETTER Task

The main effect for the factor session ($F(1, 29) = 4.79$, $P = .036$) and Hand ($F(1, 29) = 26.74$, $P < .0001$) was significant, as was the interaction between these

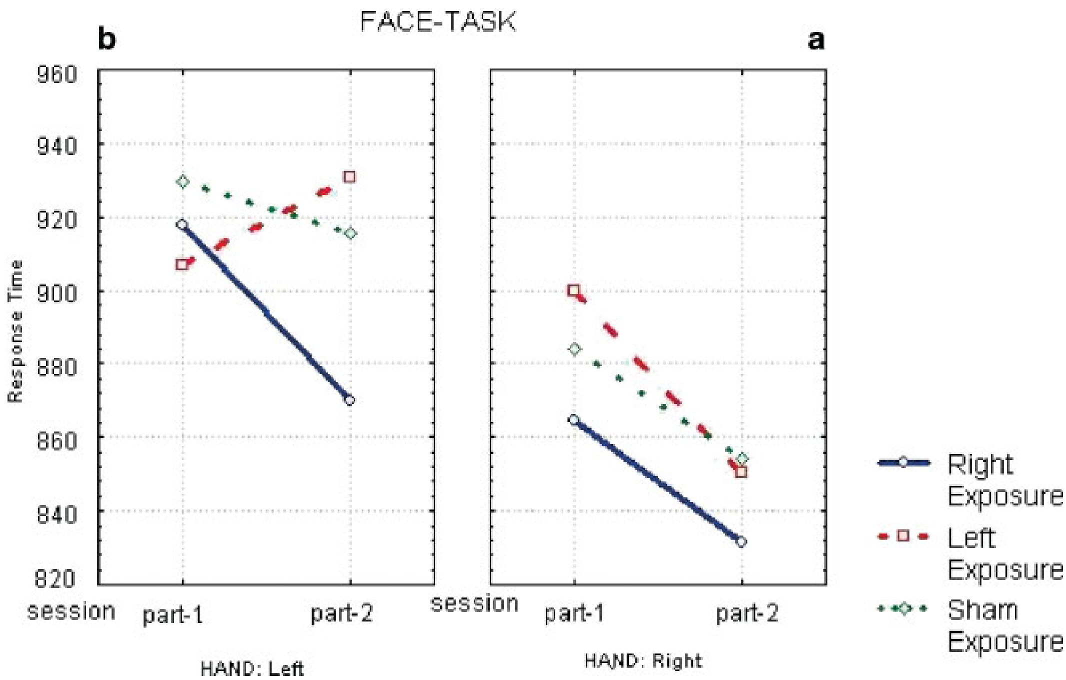

Fig. 6. Response times in milliseconds—left hand response (**b**) and right hand response (**a**)—"FACE" task. Triple interaction between exposure, session, and side was significant. For three of the exposure conditions, a reduction in the response time from the first to second session was observed. Only in the setup in which the exposure was to the left side and the left hand responded was the response time prolonged.

factors ($F(1, 29) = 9.54$, $P < .005$). Subject improvement from the first to the second part of the experiment was limited to the right hand (60 ms improvement for the right hand as opposed to 0 ms for the left hand—see Fig. 7). The results also indicate a trend similar to the FACE experiment—RTs in the left hand were increased under the left side exposure condition (by 13 ms—from 1014 to 1027 ms) as opposed to a slight decease in RT in the right side and sham exposure (2 and 9 ms respectively). This trend was not significant. It is possible that the effect of RFR is less evident on the average RT analysis, but it may still affect other parts of the RT distribution [Ratcliff, 1979]. In order to verify this point, we reanalyzed the data, this time using the 25th (fast RT) percentile as the independent variable. The left-side exposure condition slowed left hand responses by 14 ms as opposed to acceleration for the right side and sham exposure conditions (15 and 29 ms, respectively). For left hand responses, the left exposure condition was significantly slower than sham exposure in the second part of the experiment ($F(1, 29) = 4.28$, $P = .04$). This difference was not significant in the first part of the experiment, $F < 1$.

Results for the SPAT Task

The only significant observable effect was the main effect for the factor of responding hand ($F(1, 29) = 7.75$, $P < .01$). Right hand responses were 9 ms faster than left hand responses (340 and 349 ms, respectively). Importantly, the same trend for the left side exposure condition appeared also in this experiment (see Fig. 8): left hand responses were slowed down by 5 ms from the first to the second part of the experiment (from 349 to 354 ms), but under the right side and the sham exposure conditions, the left hand responses was accelerated (2 and 9 ms, respectively). The difference between the left side exposure condition and the sham exposure condition was significant in the second part of the experiment ($F(1, 30) = 6.43$, $P = .01$), but this difference was not significant in the first part of the experiment, $F < 1$.

Results for the SIMON Task

The ANOVA was the same as in the previous analysis, but it included the variable compatibility (compatible vs. incompatible responses) as an additional independent variable. The main significant effect was the difference between the examination sessions ($F(1,29) = 10.86$, $P < .005$), namely: the first part of the experiment was on the average, 24 ms faster than the second part.

Another effect observed was the so-called Simon effect [Simon and Rudell, 1967; Simon, 1990]—the compatibility between the visual stimulus side and the

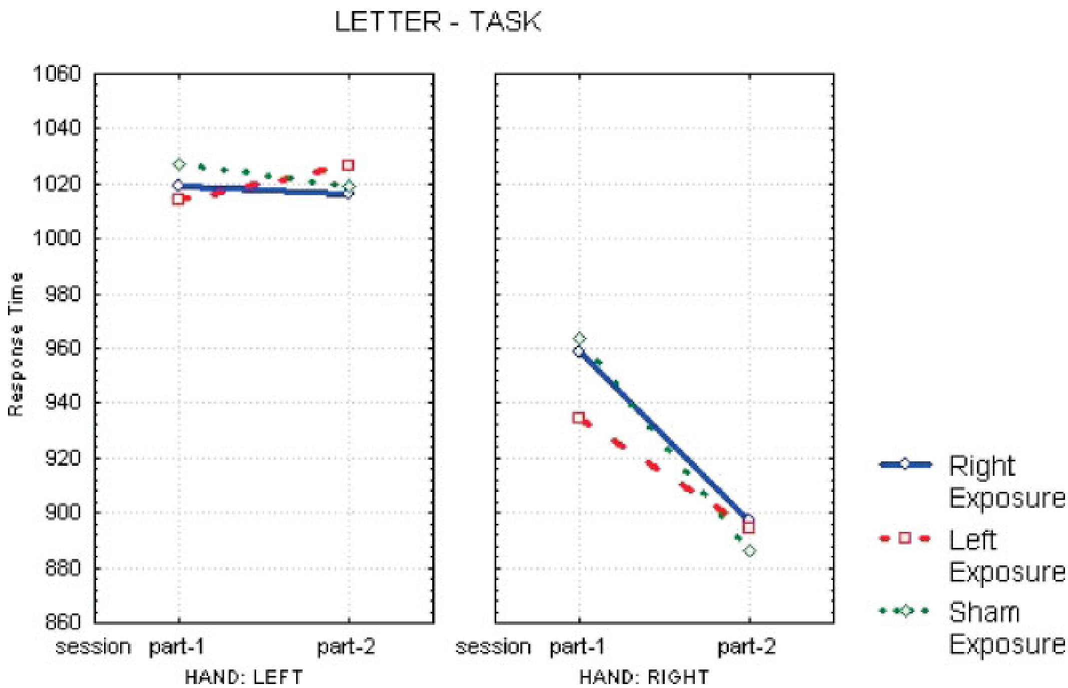

Fig. 7. Response times in milliseconds—first and second sessions—LETTER task.

responding hand ($F(1, 29) = 7.06$, $P = .01$), namely: compatible responses were 16 ms faster than incompatible responses (from 499 to 515 ms). There was no indication of any effects of RFR either in the average RT analysis or in the fast RT analysis.

DISCUSSION

The scientific literature dealing with the effects of low intensity radio waves emitted by cellular handsets shows a growing interest in the existence of cognitive

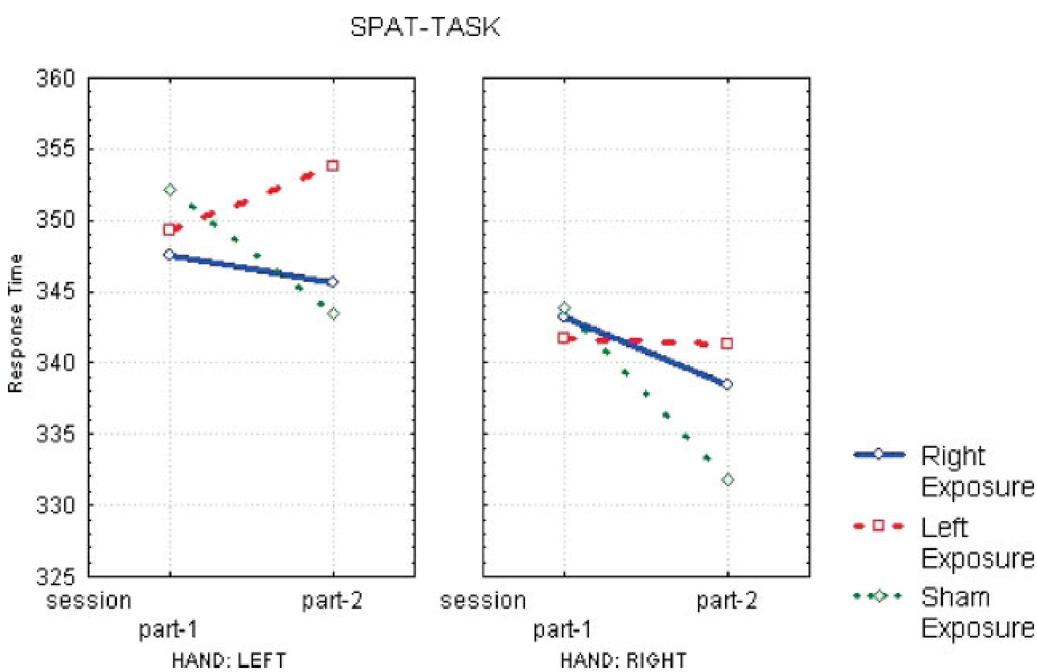

Fig. 8. Response times in milliseconds—first and second sessions—SPAT task.

effects. This is due to the assumption that cognitive functions might express very weak basic effects, if they exist, in an observable manner, because of CNS amplification.

Of these effects, the linkage between RFR exposure and RT to external stimuli has been previously examined. In particular, Preece et al. [1999] and Koivisto et al. [2000a,b] reported a shortening of the RT. Some work on verification of these reports failed to confirm their findings [Haarala et al., 2003, 2004].

In these studies only one side of the head was exposed: the left side [Preece et al., 1999; Koivisto et al., 2000a,b; Haarala et al., 2003, 2004] and the right side [Krause et al., 2000]. The responding hand was the right hand in some works [Koivisto et al., 2000a,b; Haarala et al., 2003, 2004], while in the other publications this was not clearly specified.

In the present work, we thus added specific examinations of possible differences between right/left side exposures and right/left responding hand.

We considered these details to be of relevance, due to the differentiation between the right/left brain hemispheres functions.

The present work is, to the best of our knowledge, the first attempt to examine directly these two responding conditions. To achieve these purposes, we used two phones, placed simultaneously on both sides of the head, and in fact, our results indicated that the effect of RFR was evident only in the left head side exposure and left hand responding combined condition.

The statistically significant finding was a slowing effect in left hand responses under left side RFR exposure condition only (found in the spatial item recognition task—"FACE"). This effect became evident only in the second part of the experiment (namely: after an hour of test, of which 40 min were under full power exposure). The same trend was also observed in the spatial compatibility task—"SPAT", but was significant only in the specific comparison analysis.

While the effects of RFR were not evident in all experiments, it is possible that the dependent variable of average RT is not sensitive enough to detect those effects [Ratcliff, 1979]. In this respect we have shown that at least in one task (Verbal item recognition—"LETTER") the effects were not apparent in the usual average RT but were detectable in other parts of the RT distribution. Specifically, we found changes on the 25th percentile (the fast part of the RT distribution).

It is noteworthy that although all the detected effects were expressed in left hand slowing, and appeared under left side exposure, we cannot state that a hemisphere dependence was detected, as the functions affected are related to activities of both hemispheres.

The origin of the differences between our results and the former studies is unclear, and could result form several reasons such as: the exposure methodology—right and left hemispheres, the responding hand—left or right, the exposure time, and the differences in the cognitive tasks. These differences seem to be significant and should be examined in future studies.

It can be concluded that more work is required to verify our results and to reconcile the differences between our study, and the former studies in which an opposite effect, or no effect were found. In addition, the involvement of confounding factors must be examined further.

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