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Low Intensity Magnetic Field Influences Short-Term Memory: A Study in a Group of Healthy Students

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This study analyzes if an external magnetic stimulus (2 kHz and approximately 0.1 μT applied near frontal cortex) influences working memory, perception, binary decision, motor execution, and sustained attention in humans. A magnetic stimulus and a sham stimulus were applied to both sides of the head (frontal cortex close to temporal–parietal area) in young and healthy male test subjects ($n = 65$) while performing Sternberg's memory scanning task. There was a significant change in reaction time. Times recorded for perception, sustained attention, and motor execution were lower in exposed subjects ($P < 0.01$). However, time employed in binary decision increased for subjects exposed to magnetic fields. From results, it seems that a low intensity 2 kHz exposure modifies short-term working memory, as well as perception, binary decision, motor execution, and sustained attention. Bioelectromagnetics. 37:37–48, 2016. © 2015 Wiley Periodicals, Inc.

Key words: electromagnetic fields; working memory; reaction time; Sternberg task; learning deficit

INTRODUCTION

There is growing concern about biological effects of exposure to low levels of magnetic field (MF). MFs in audio frequency range 20 Hz–20 kHz are found near any electrical and electronic equipment, and are omnipresent due to now widespread use of devices inducing such fields. These fields present within the home are generated by appliances (e.g., washing machines and refrigerators), televisions, mobile telephones, desktop computer monitors, and energy-efficient fluorescent lighting fixtures. Such fields contain a large spectral content and are aptly named "dirty electricity" [Havas, 2008]. Kilohertz signals are used in power-line communications (PLC) to monitor electricity and gas in smart meters [Galli et al., 2008]. Fields in the kilohertz range are also present near audio devices such as audio headphones and ear buds. Portable digital music devices (MP3 players) such as the iPod (Apple, Cupertino, CA) have become increasingly common, with more than 100 million units sold in 2007, and some 350 million up to September 2012 [Costello, 2014a,b]. Depending on model, these audio devices produce an MF induction close to the brain's temporal lobe at about 0.1 μT, 20 Hz–20 kHz. These devices can produce clinically significant magnetic interference when placed near an implanted pacemaker [Lee et al., 2009]. It is plausible that these low levels of MF (~0.1 μT, 20 Hz–20 kHz) have an adverse effect on the human nervous system and influence behavior. Russian standards of electromagnetic field (EMF) exposure are much lower than in Western countries largely because of detected effects on the nervous system of these types of EMF signals [Presman, 1970; Szmigielski, 1989]. Several studies have shown influence of MFs on behavior, motor activity, and neurotransmitters in the human brain [Trzeciak et al., 1993; Chance et al., 1995; Pesic et al., 2004]. Results from human studies [Trimmel and Schweiger, 1998] and

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Conflicts of interest: None.

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animal studies [Lai, 1996; Lai et al., 1998; Sienkiewicz et al., 1998a,b; Lai and Carino, 1999] have shown exposure to MF may influence cognitive functions.

Trimmel and Schweiger [1998] found immediate reduction of cognitive performance under the influence of an MF of 1 mT (±10%), 50 Hz, in the head area. However, effects were modulated by self-perception of sensitivity to MF. These effects were found to be more pronounced in sensitive human test subjects. The work of Lai [1996] and Lai et al. [1998] showed that a 60 Hz–0.75 mT MF exposure before learning routines impaired spatial memory in laboratory test rats.

MF effects on the brain's electrical activity have been reported by other researchers in the field [Bell et al., 1991; Marino et al., 1996; Dobson et al., 2000; Lyskov et al., 2001; Marino et al., 2004]. It was recently shown that an MF stimulus (3 μT, 60 Hz) was capable of worsening improvement associated with practice [Corbacio et al., 2011]. Although a clear mechanism of MF on human cognition has yet to be established, it has been speculated that MF interferes with neuropsychological processes responsible for short-term learning—as supported by the brain's synaptic plasticity.

Two pioneering studies examined effects of MFs on spatial learning in rodents, showing that brief exposure to relatively weak time-varying MF (60 Hz–0.1 mT) could affect spatial learning and memory in rodents [Kavaliers et al., 1993, 1996]. Kavaliers et al. [1993, 1996] showed sex differences in effects of MFs and raises a possible mode of action through alterations in opioid activity. Other researchers evaluated MF effects on post-training consolidation and retrieval processes [McKay and Persinger, 2000]. Their study evaluated whether acute exposure to 2 or 8 mT influenced consolidation and retrieval of spatial memory in laboratory test rats.

There is acute paucity of studies on influence of MF fields on human brains and cognition, in particular, MF effect on memory and behavior. The example of the effect of a 2 kHz signal is especially interesting as this frequency is inside the sound band (20 Hz–20 kHz). Typical headphones and earbuds are audio transducers and generate a sound signal using an electrical signal of the same frequency. The current that drives this signal is inside the KHz range and this current is the source of the associated MF. These devices produce a low intensity MF field near areas of the brain involved in memory processes and especially short-term memory. Working memory (WM) is defined as a system that manipulates transient information as a part of human memory. WM is assumed to sustain neuronal activity up to several tens of seconds in the pre-frontal cortex, but also in other areas (e.g., the parietal cortex) [Babiloni et al., 2004; Passingham and Sakai, 2004].

There is scientific consensus about difficulties in describing brain function and behavior, as variables that assess behavior are not sensitive enough to measure changes in brain function [Kurokawa et al., 2003; Cook et al., 2006]. The "Sternberg paradigm" is especially suitable for detecting minimal cognitive changes [Sternberg, 1966, 1969, 1975]. Cognitive paradigms are always a difficult choice due to lack of standardized rules and the fact that variations can be caused by, among other things, choice of stimuli, timing, instructions given to subject, and expected responses [Baddeley, 1992].

Sternberg item recognition paradigm (SIRP) provides a computerized chronometric method for measuring working memory, as well as perception, binary decision, and motor execution. SIRP is a choice reaction time test that mainly dissociates motor and cognitive components in response times. Accurate responses are predicated upon a temporarily stored representation of targets that must be maintained in working memory for trial's duration. Sternberg [1966] showed that a linear relationship exists between response time and number of targets that the subject must keep "on-line." The slope of the linear function provides a measure of the cognitive component of response time (i.e., increasing response time linearly with each increment in working memory load) [Sternberg, 1966, 1969, 1975; Jensen and Lisman, 1998]. Zero intercept provides a measure of perception, binary decision, and motor execution of response time. Principal functional stages can be characterized as: (1) encoding of stimulus; (2) serial memory scanning; (3) binary decision about nature of response; and (4) response organization and execution.

In clinical studies, sustained concentration on a prolonged task has been widely used to assess vulnerability of attention [Robertson et al., 1997; Manly et al., 1999]. Indeed, it has been reported that a patient population with difficulties in sustaining attention exhibited frequent errors when compared with normal controls [Bellgrove et al., 2006; Johnson et al., 2007]. Measuring attention is somewhat more complicated, as attention is not a single quantifiable factor and significantly overlaps with working memory.

The present work analyzes immediate effects of an external ($\sim$0.1 μT, 2 kHz) MF stimulus on these neurological processes, particularly on WM. We designed an experimental procedure to analyze influence of MF exposure on response time (RT) of subjects performing the Sternberg test. The statistical tool used to measure this influence is a multiple regression of RT on exposure to radiation (binary variable) and two variables related to SIRP: number of letters to memorize (set size) and type of letter (memorized or non-memorized). The present work is significant because for the first time, Sternberg's test was used to analyze effects of an MF on WM. To our knowledge, this is the first time that human exposure to an MF in the KHz range was explored, as previous similar work was carried out with animals and also at different MF frequencies. These are the main novelties of the present research.

MATERIALS AND METHODS

Participants

A group of 75 healthy male subjects (students of the same academic course from the University of Valencia in Spain) were recruited for the study. There were few female candidate students available and so female volunteers were not included to maintain the homogeneity of test group.

To analyze health status and current exposure to electronic equipment, physiological data (e.g., age, weight, and height), information on health-related issues, and use of electronic devices was collected through a questionnaire. Medical symptoms related with headaches, dizziness, sleeping difficulties, tiredness, restlessness, concentration difficulties, joint pain, nervousness, nausea, lack of appetite, feeling sad, loss of memory, skin conditions, and visual and hearing difficulties were duly recorded. Frequency of these symptoms was classified as never, rarely, often, and always. A question was also posed about general health status and scored in the range: poor (0); acceptable (1); good (2); very good (3); and excellent (4). In addition, participants were asked about alcohol and tobacco consumption, use of medication (chronically and 24 h prior to test). If this question had a positive answer, participant was discarded from experiment. Finally, use of current electronic devices (such as computers and mobile telephones) was surveyed—as well as type of internet access (wireless or wired).

Volunteers were told that exposure level would be far below safety regulations in Europe (Directive 2013/35/EU) and Spain. They signed an agreement to participate in the experiment, which was conducted in accordance with the Declaration of Helsinki [World Medical Association, 2015] and in accordance with Act 14/2007 (Spain) for biomedical research

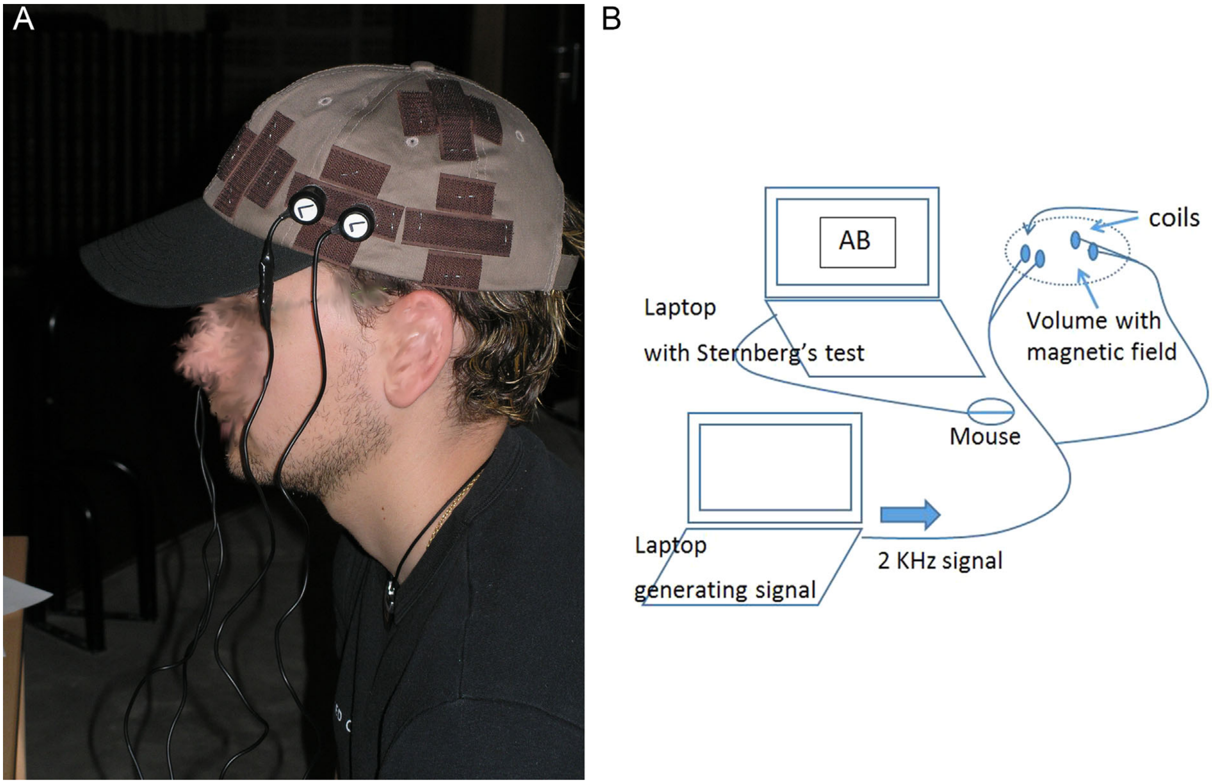

Fig. 1. Exposure system. (**A**) Subject with exposure system. (**B**) General view of experimental set-up.

[Anonymous, 2015]. This agreement was approved by the Ethical Committee of the University of Valencia (Burjassot, Valencia, Spain).

With 65 volunteers, two groups were constituted: one group with MF exposure and the other with no MF exposure. All subjects were tested individually by the same examiners in a double-blind approach, that is, neither test subjects nor examiners knew if they were exposed or not to MF.

Estimation of Current Exposure Levels From Electronic Devices

Computer use was estimated by accounting hours per day in front of an active computer screen. Type of internet access (wired or wireless) was also analyzed. Use of mobile telephone was estimated through a model developed to estimate relative exposure levels on a scale of 0–10. To assess radiofrequency exposure [Kim et al., 2006] we used parameters such as time per day, hands-free usage, extension of antenna, specific absorption rate of mobile telephone, and type of device (flip or fold).

Exposure System

MF for the exposure was generated using the soundcard of a laptop computer and four coils. An HP Compaq nc6120 notebook computer managed with the Cool Edit Pro software (Syntrillium Cool Edit Pro 2.0 Audio Editing Software, Adobe Systems, San Jose, CA) was used to generate a 2 KHz current from the sound card. The HP Compaq nc6120 notebook was supplied by Hewlett-Packard (Barcelona, Spain). The current from the sound card was driven in parallel through two pairs of copper cables to two pairs of coils. Each pair of coils was attached with Velcro fasteners at each side of a cloth cap worn by each test subject. Figure 1A shows position of coils, and positions of coils on cap. Four coils were symmetrically located on both sides of the head, attached to the cap near the frontal-parietal sides of the head and next to the temporal area. Figure 1B shows a general view of experimental set-up.

Coils consisted of 800 turns of AWG-40 copper wire with a resistance of 96 ohms and inductance of 4.7 mH. Coils were 6.5 mm in length and had an average diameter of 7 mm (supplied by RS Amidata, es.rs-online.co). The sound card current from the nc6120 was applied to coils and regulated with the Cool Edit Pro software. MF exposure applied with coils was deduced from voltage generated by sound card, impedance, and length and radius of coils. Voltage was measured with a TDS 3032 oscilloscope supplied by Tektronix (Beaverton, OR). Each coil carried approximately 0.0062 A. The calculated MF was 0.10 μT at 7 cm from the edge of a single coil using analytical expression of MF along axis of a coil [Kraus, 1986]. The MF from the two coils in the head volume cannot be calculated with analytical expressions and was numerically calculated using finite differences with a numerical integral of the Biot–Savart law [Kraus, 1986; Pozar, 1994]. Figure 2A shows numerically calculated MF in a

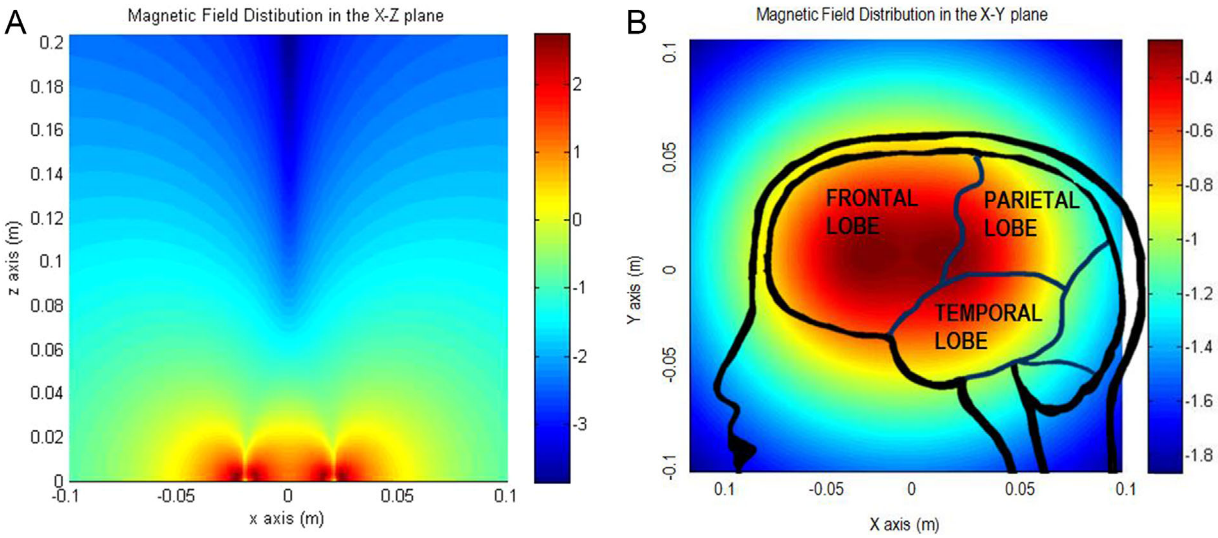

Fig. 2. MF calculated with finite differences. Source is a pair of coils with the axes separated by 4 cm simulating our exposure system. Axes of the coils are in the x-z plane. Color scale is log10 (ıBı/1 μT). (**A**) In a plane that contains the axes of the coils, x-z plane. (**B**) In a plane perpendicular to the axes of the solenoids at a distance of 4 cm from the edge of both coils, x-y plane. Overlaid is a sketch of the head and brain parts under exposure.

plane that contains the axes of the coils, and Figure 2B shows MF in a plane perpendicular to the axes of the coils at a distance of 4 cm from the edge of both coils. Numerical calculations provide an MF of $\geq 0.1\ \mu T$ in an approximate area of a 7 cm radius at 4 cm distance from the coil edges (Fig. 2B), and this area decreased to a radius of 6 cm at a distance of 6 cm, and calculated average MF in a $10 \times 10 \times 7\ cm^3$ volume next to the coils was $0.110\ \mu T$ (spatial variability $\pm 0.025\ \mu T$). Coils were attached to the cap, and taking into account the air and tissue of the cap, the edges of the coil were approximately 1 cm from the skull. This exposure influences the prefrontal cortex next to the temporal–parietal area, and Figure 2B shows a sketch of the head and brain parts overlaid with the MF calculations.

The MF was also measured using an EFA-300 MF meter (Narda Microwave, Hauppauge, NY). The background level was measured using the EFA-300 with a B-100 cm^2 probe to an average 13 nT (band 5 Hz–32 KHz). Measured MF with probe in contact with coils was in agreement with numerical calculations.

The laptop computer was positioned 2 m from the position of the volunteer when seated in a large classroom. The position was at a minimum distance of 10 m from walls. Classroom was acoustically isolated with typical materials in walls.

Ambient noise was measured with a sound meter (Cesva SC-30, CESVSA Instruments, Barcelona, Spain) during each test run. Average noise level during all test runs was ~45 dB. Nearest noise source was low-level street traffic some 50 m from the classroom.

Tests were made some nine meters from any wire conducting electricity, and illumination was natural sunlight. All experiments were conducted between noon and 1 p.m.

Exposure was switched on at beginning of Sternberg test and turned off when test was finished. Time exposure was dependent on duration of Sternberg test and was around 11 min.

The laptop computer used for stimulus and laptop computer used for Sternberg test were battery operated to minimize presence of external MFs.

Sternberg Test Description

An Easynote laptop computer (Packard Bell BV Europe, Hertogenbosch, the Netherlands) was used for presenting information and recording test subjects' responses. Items were presented on the screen of the laptop computer (dimensions $28.5 \times 21.5\ cm^2$) in Arial font (3 cm high) and viewed from a distance of approximately 60 cm. Responses were given using two hand-held thumb-keys in the mouse. The mouse was on preferred hand side (right or left), the key for positive decisions corresponded to the right side of the mouse, and the key for negative decisions corresponded to the left side of the mouse.

Symbols that the test subject had to memorize were termed target symbols (TG), and when these were shown on the screen they should lead to a positive decision. Symbols not memorized were termed non-target symbols (NTG) and these should lead to a negative decision. Details of memory scanning of the Sternberg test are described elsewhere by Brand et al. [1992]. The method of TG and NTG selection was adapted from the work of Logan [1978]. The pool of symbols (or stimuli) consisted of 21 consonants of the alphabet (shown in capitals). TG set consisted of 9 different letters and NTG set contained 12 different letters. TG items in one condition of the test never appeared as NTG in another condition, that is, TG letters for a given size set (SZ) did not appear as NTG in the following SZ or SZ + 1.

Subjects were asked to memorize items of a set consisting of 1, 2, 3, or 4 letters (i.e., SZ = 1, 2, 3, or 4) presented for 5 s. These letters were TG symbols. Thereafter, a series of letters were presented one after another. Each letter was presented 1 s after the previous response and displayed for a maximum of 1 s. RT was defined as time from stimulus onset to the moment that a mouse key was pressed. The subject had to press the yes button (right mouse button) when the presented letter belonged to the memorized set (TG) and press the no button (left mouse button) when it did not belong (NTG). Test subjects were asked to respond as quickly and accurately as possible. Exposure/sham-exposure was double blind, and there were 34 exposed and 31 sham-exposed subjects.

For each subject under test, there were four cases of at least 60 trials, that is, maximum $4 \times 60 = 240$ total trials, corresponding to set sizes 1,2,3,4 letters (SZ = 1,2,3,4). That is, firstly with one letter (SZ = 1), secondly with two letters (SZ = 2), thirdly with three letters (SZ = 3), and fourthly with four letters (SZ = 4). Each case with a given SZ consisted of at least 60 trials; there were 48 test trials, preceded by a minimum of 12 practice trials. The test period began when there were no errors in the preceding six practice trials. There were 24 positive (TG) and 24 negative (NTG) test trials, with equal probability of occurrence of TG in 48 trials. TG and NTG were presented in the same semi-random order to each subject. No more than 3 TG or NTG appeared successively. RT of each case in each SZ (TG or NTG) was recorded on the laptop computer for further statistical analysis. The Matlab software package

(MathWorks, Natick, MA) was used for multiple regression model.

Mathematical Model and Statistical Analysis

Previous work by Sternberg [1966, 1969] showed reaction time increases linearly with WM load. The relationship of WM load to SZ was linear. In the plot of RT versus SZ, slope could be construed as extra time needed per extra item in memory scanning during WM retrieval. The zero intercept was suggested to be related to response selection, preparation, and execution.

It is reasonable to expect that the more letters to remember, the more time the brain takes to compare shown symbol with memorized symbols. In other words, if the brain works by sequencing WM (not in parallel), it will spend more time retrieving symbols in WM. If the shown symbol (NTG) does not belong to memorized set, the brain will serially scan the memory and arrive at the end of the SZ in WM without a positive output. However, if shown letter belongs to memorized set (TG case), the brain will stop scanning when the position of the symbol is reached, and this will take less time than in NTG case. Because we do not know the exact position of memorized symbols in WM, we can only assume a negative bias in RT associated with the TG case. The proposed mathematical multiple regression model is [Sternberg, 1966, 1969] as follows:

$$RT = \beta_0 + \beta_1 \cdot SZ + \beta_2 \cdot TG \tag{1}$$

Where β_0 is zero intercept: time employed in the response selection, preparation, and execution; β_1 is slope exclusively associated with SZ: extra time per extra symbol in WM retrieval and β_2: shift or bias in the zero intercept associated with the target case.

The used variables are as follows:

Set size (SZ) = {1,2,3,4}

Target case TG = 1 and non-target case NTG = 0.

The above model is widely accepted and shows the influence of two factors: binary categorical variable TG (memorized or non-memorized); and covariate SZ indicating SZ or number of letters.

The influence of an external stimulus on brain activity during the test could change RT, and this change could be related to the following:

1. Response selection, preparation, and execution [Sternberg, 1966, 1969]: this is expected as a time bias accounted with a new parameter β_2'.
2. Retrieval time per SZ: effect on retrieval time per SZ would be a direct effect on WM, this is modeled with an extra parameter to modify slope β_3'.

Our experiment was designed to detect influence of exposure to an MF (external stimulus); therefore, we introduced an additional factor in the model to account for exposure—a binary categorical variable EX (control EX = 0, exposed EX = 1). We chose a multiple regression model that estimates effect (β'-coefficients) of factors (TG, EX) and covariate (SZ) on RT, including in the model the interaction between radiation and size of target. A coefficient β' other than zero implies that the effect of the relevant factor or covariate is significant.

A new model was, therefore, established with a new variable EX, introduced in the model to account for exposure, that is, if EX = 1, subject suffers MF exposure, and if EX = 0, subject has had no MF exposure. The change in the time used for response selection, preparation, and execution is expected to be a constant bias, expressed in the new parameter β_2'. Effects in retrieval time from WM are accounted for with the new parameter β_3', other parameters were unchanged from the model in (1), however they were renamed: $\beta_0' = \beta_0$, $\beta_1' = \beta_1$, $\beta_4' = \beta_2$.

Our multiple regression model to analyze effects of exposure, therefore, becomes

$$RT = \beta_0' + \beta_1' \cdot SZ + \beta_2' \cdot EX + \beta_3' \cdot SZ \cdot EX + \beta_4' \cdot TG \tag{2}$$

Where coefficients are:

β_0', zero intercept; β_1', slope exclusively associated with SZ;

β_2', shift in zero intercept associated with exposure (EX);

β_3', change in slope due to interaction between size and exposure; and

β_4', shift in zero intercept associated with target case.

Variables are:

Set size SZ = {1,2,3,4}.

Target case TG = 1, non-target case TG = 0.

MF exposed: EX = 1, non-MF exposed: EX = 0.

RT is registered in milliseconds for all SZ and TG cases. Because testing protocol is double-blind, the variable EX is known only at end of experiment.

TABLE 1. Demographical and Health Status Average Values and Standard Deviation for Both Groups, With Corresponding Statistical Test

	Not MF-exposed (control)	($N = 31$)	MF-exposed	($N = 34$)			
t-Test	Average	SD	Average	SD	*t*	*P*-value	
Age, years	23.61	2.26	22.79	2.52	1.374	0.174	
Body mass index, Kg/m^2	25.84	4.16	25.11	3.68	0.755	0.453	
Mass (Kg)	84.32	17.30	79.00	10.46	1.483	0.144	
Height (cm)	180.29	10.19	177.59	8.61	1.158	0.251	
Daily computer use (h/day)	3.95	2.32	4.76	2.46	−1.366	0.177	
Percentage over the group of video gamers	64.52%	0.49	70.59%	0.46	−0.516	0.608	
Use of mobile telephone[a]	7.07	0.75	7.13	0.64	−0.325	0.746	
Non parametric test					Mann–Whitney U	*Z*	*P*-value
Headache[b]	1.16	0.78	1.24	0.65	493.000	−.490	0.624
Difficulty/sleeping[b]	0.87	0.89	1.21	0.85	406.000	−1.709	0.088
Tiredness[b]	1.42	0.92	1.38	0.74	517.500	−0.135	0.893
Restlessness[b]	0.77	0.85	.97	0.90	463.500	−0.895	0.371
Difficulty/concentration[b]	1.45	0.93	1.41	0.93	524.000	−0.042	0.967
Nervousness[b]	1.16	1.04	1.38	1.18	473.500	−0.733	0.463
Joint Pain[b]	0.81	0.95	0.85	0.78	491.000	−0.506	0.613
Nauseas[b]	0.16	0.37	0.24	0.50	501.000	−0.507	0.612
Lack appetite[b]	0.26	0.51	0.35	0.54	477.500	−0.834	0.404
Feeling sad[b]	0.35	0.61	0.41	0.78	523.500	−0.059	0.953
Loss memory[b]	0.55	0.85	0.65	0.81	478.500	−0.721	0.471
Skin problems[b]	0.26	0.51	0.50	0.83	454.500	−1.196	0.232
Visual problems[b]	0.19	0.54	0.41	0.66	429.500	−1.741	0.082
Hearing problems[b]	0.06	0.25	0.26	0.57	450.500	−1.676	0.094
Dizziness[b]	0.16	0.45	0.24	0.50	488.000	−0.787	0.432
Cardiovascular problems[b]	0.16	0.45	0.03	0.17	474.000	−1.507	0.132
Health status[c]	2.94	0.68	2.74	0.67	454.000	−1.077	0.281

[a] Relative exposure to mobile telephone score 0–10 following the work of Kim et al. [2006].

[b] Frequency of the medical symptom (score 0–4 in all symptoms).

[c] Score 0–4, poor = 0, excellent = 4.z

TABLE 2. Average Values of RT for Each Case With the Corresponding Standard Error

		Exposed		Not exposed	
TG	SZ	Mean	SE	Mean	SE
Target	1	398.73	3.04	403.16	3.78
	2	440.60	3.50	440.81	3.88
	3	463.09	3.86	458.38	4.03
	4	478.57	3.92	471.46	3.93
Non-target	1	425.93	3.45	438.53	3.96
	2	469.33	3.84	479.63	4.10
	3	493.93	4.05	491.78	4.56
	4	502.82	4.03	502.09	4.41

RESULTS AND DISCUSSION

Total time spent by volunteers in the Sternberg test program was around 11 min. All test participants concluded the trial successfully without any observed adverse side effects.

Differences between groups according to health status parameters, age, and body mass index, recent medication, and use of electronic devices were analyzed. As shown in Table 1, general health and behavioral profiles of the two test groups were similar.

Average RT and standard error are shown in Table 2 to give an overview of obtained results. Average values of the RT versus SZ with the corresponding standard error are shown in Figure 3A for exposed and non-exposed subjects. Regression lines obtained from RT data for both subjects are significantly different, and these are plotted in Figure 3B and coefficients presented in Table 3. Statistical results of the multiple regression model are shown in Table 3, and there is statistical significance in all the parameters β' that are different from zero ($P < 0.01$). An analysis of obtained parameters provides the following discussion. Parameter $\beta_0' = 428.065$ ms is time employed in response selection, preparation, and execution. $\beta_1' = 19.403$ ms is retrieval time added for each additional unit in SZ, and parameter $\beta_4' = -28.542$ ms is associated with target condition. There is still debate about the search pattern in the target case (or yes case). Corbin and Marquer [2009] suggested different search models depending on subject (these being between serial "self-terminating" and exhaustive search and parallel search). The purpose of the present research was to analyze changes in RT with MF exposure, regardless of type of search that may occur. The present experimental results are consistent with previous studies on the Sternberg paradigm that showed a short retrieval time per item in the yes answer (TG case), and a steeper slope for the multiple regression model. Calculated β_4' parameter (-28.542 ms) would account globally for the TG condition.

The main interest of the present work is in the parameters $\beta_2' = -15.367$ ms ($t = -3.132$, $P < 0.001$) and $\beta_3' = 6.279$ ms ($t = 3.506$, $P < 0.001$). The β_2' is the zero intercept shift associated with the exposure. Zero intercept is interpreted as duration of encoding

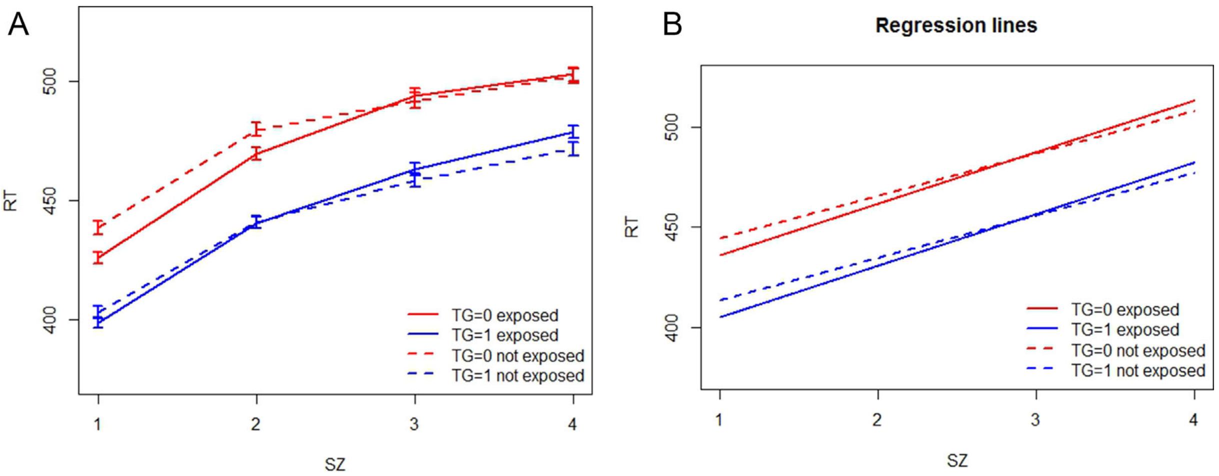

Fig. 3. (**A**) Average values of reaction time (RT) versus size set (SZ) with corresponding standard error for exposed and non-exposed subjects, for target case (shown item with a given set size to be memorized) and non-target case (shown item with a given set size not to be memorized). (**B**) Regression lines from multiregression results shown in Table 3. Solid lines are exposed while dashed lines are non-exposed; blue shows target case (TG = 1); and red shows non-target case (TG = 0).

TABLE 3. Multiple Regression Model (Eq. 2): Coefficients, Standard Error, *t*-Value, and Associated *P*-Value

Variable	$\beta'_{1-2-3-4}$	Std. error	*t*-Value	*P*-Value
Intercept	428.065	3.740	114.465	0.000
SZ	19.403	1.319	14.706	0.000
EX	−15.367	4.906	−3.132	0.002
SZ*EX	6.279	1.791	3.506	0.000
TG	−28.542	1.997	−14.295	0.000

and motor response process, and exposure produced a negative bias of 15.367 ms, that is, exposure reduced RT by 15.367 ms. From our model, this time reduction in RT is produced in time used for encoding and motor response process. These results are similar to results of Koivisto et al. [2000] using a digitally modulated 902 MHz signal. The similitude of effects could be explained as a signal demodulation in brain tissues that extract kHz signals from modulated digital signal.

Results seem contradictory because time per memory item is longer for exposed group ($\beta_3' = 6.279$ ms, $t = 3.506$, $P < 0.001$). The parameter β_3' is significant, this indicates a significant interaction between SZ and EX, thus showing that exposed subjects (EX = 1) displayed significantly worse responses than unexposed (EX = 0) subjects because for each unitary increment in SZ, the RT increased 6.279 ms. The slope for unexposed subjects (EX = 0) is $\beta_1' = 19.403$ ms per SZ, and slope for exposed (EX = 1) is $\beta_1' + \beta_3' = 25.6820$ ms per SZ. These results are in line with results from Lai et al. [1993] and Lai [1996] in which rats were exposed to an MF immediately before each training session and exposure retarded learning significantly. This could be explained as impairment of WM. According to Lai et al. [1993], these effects were related to changes in cholinergic activity in the frontal cortex.

WM involves a short-term storage capacity and interplay between neural systems for perception and manipulation of stored information with the objective of guiding neural systems for action [Baddeley and Logie, 1999; Fuster, 2003; Ranganath and D'Esposito, 2005; Inoue and Mikami, 2006]. Concretely, the maintenance of a visual object in WM is associated with persistent activation of object-selective neurons through activation of visual representations in the inferior temporal cortex [Fuster, 2003; Ranganath and D'Esposito, 2005]. These visual object representations can be activated by inputs from prefrontal regions, which play critical roles in WM [Goldman-Rakic, 1987; Funahashi and Kubota, 1994] and by inputs from the hippocampus and medial temporal neocortex [Fuster, 2003; Ranganath and D'Esposito, 2005]. Moreover, the prefrontal cortex, medial temporal neocortex, and hippocampus activate temporal memory networks to guide goal-directed behavior, or in our case, a selective motor execution. Therefore, placing MF exposure on the temporal–parietal–prefrontal areas should target main networks implied in WM.

There is neuropsychological evidence of deficits in WM associated with alterations in the frontal lobe: positron emission tomography scans and functional magnetic resonance imaging data have shown that the dorsolateral pre-frontal cortex is most active when working memory tasks are performed [Bunge et al., 2000]. If memory effect is related to blood flow in the brain, this would be related to results of Huber et al. [2005]. The effect described in that work depends on spectral power in amplitude modulation of the radiofrequency carrier. Low-frequency components from pulse modulation of the radiofrequency signal were necessary to induce alterations in brain physiology [Huber et al., 2005]. The similitude in effect could be explained if biological tissue could "detect" or "demodulate" the radiofrequency modulated carrier, as happens in a solid state junction, in diodes, or transistors in radiofrequency receivers [Pozar, 1994].

Motivation and motor reaction times interfere with performance [Weintraub, 2000] and our study shows that MF exposure could induce these changes. MF exposure could be a short-term aversive stressor, and it is plausible that MF exposure could influence the mood of our test volunteers as mood is generally known to affect how information is processed [Estrada et al., 1994; Fiedler, 2004; Isbell, 2004].

Errors in completing the Sternberg task were produced by all subjects. Errors were classified as either test subject mistakes in providing correct answer or test subject omission in providing an answer. Average and standard deviation of both types of errors were calculated for each test group. As shown in Table 4, neither of these two types of error was found to be statistically significant. The error occurring in each group indicated that MF exposure does not produce an excessive increase in number of

TABLE 4. Descriptive for the Two Error Types: Mean (Standard Deviation), and the Significance of the Corresponding *t*-Test

Type of error	Not MF-exposed ($n = 31$)	MF-exposed ($n = 34$)	Test
Mistaken	7.30 (5.95)	7.65 (6.36)	NS
Omissions	0.89 (1.41)	0.46 (0.69)	NS

mistakes, or affect capacity of attention related to number of omission errors. Conversely, it seems that MF exposure reduces number of mistakes. However, results for error counting were not statistically significant ($P > 0.05$). As the total number of errors was similar in both groups, we may reasonably conclude that sustained attention was unaffected by MF exposure. It has previously been reported that subjects with pre-existing impaired attention exhibited more frequent errors when compared with normal controls [Bellgrove et al., 2006; Johnson et al., 2007].

In our literature review, we observed that there were reports of significant changes in physiological measures—but few studies on cognitive effects (e.g., [Cook et al., 2006]). Some behavioral measurements were not sufficiently sensitive to show changes in physiological performance. Moreover, in some cases, brain areas studied were not sufficiently responsive to exhibit measurable physiological changes—and most behavioral studies relied on frontal or temporal functions [Cook et al., 2006].

The Sternberg paradigm detects minimal cognitive changes in the short-term. Our preliminary study shows that MF exposure (around 0.1 μT, 2 kHz) modifies short-term WM through changes in perception, binary decision, motor execution, and sustained attention. Furthermore, absence of differences between test groups in reference to personal variables enhances the validity of this study, as the Sternberg test is intrinsically affected by these conditions [Houx et al., 1991].

If changes in RT and alterations in WM were considered a dysfunction of the nervous system, then the next step—given that significant changes in brain activity were detected—is to evaluate the severity of observed effects.

Biochemical changes supporting this assessment can be found in Lai and Carino [1999]. It is accepted that MF exposure at 50–60Hz affects endogenous opioid systems, as well as other neurotransmitters [Shin et al., 2007; Chung et al., 2015]. The neurotransmitter dopamine and endogenous opioid systems (see Izquierdo [1991]) have been implicated in complex cognitive functions such as WM and cognitive control. Dopamine systems—depending on specific levels and the brain region targeted (probably striatum and prefrontal cortex [Cools and D'Esposito, 2011])—seem to have inhibitory effects on learning and memory processes. Opioid antagonists facilitate spatial and other forms of memory acquisition [Kavaliers et al., 1993]. At different frequencies, MF could modulate WM to adversely affect the human learning process. Long-term MF exposure (at our experimented levels) could also induce an acute learning deficit.

CONCLUSIONS

Short-term memory, or the ability to hold an item of information transiently in the human brain for as-needed recall, was altered in our experiments. This finding indicates that real stimulation by low-intensity MF could hamper human neural processing related to response selection, preparation, and execution. In view of these preliminary study results, we suggest a warning be given to people with frequent voluntary exposure to KHz range signals. Low-intensity MF is similar to that generated by most ear buds and lightweight headphones used with MP3 portable music players. For instance, these devices have an impedance of about 30 Ω at 30 mW per channel [Stereophile, 2015] and produce an MF $\sim$0.10 μT inside the brain from both sides of the head. This level of MF could induce learning problems among young users—and not only from loud noise. Furthermore, a warning message should be given for home use of PLC for internet access through an electrical power line. Moreover, we are particularly concerned about future deployment of PLC in general public services for remote control of electricity meters and other smart meters. Ultra narrow band PLC frequencies are below 3 KHz and narrow band PLC is within 3 KHz–500 KHz. PLC-generated MF is low attenuated in the environment and its penetration into houses cannot be avoided. PLC signals may need to be optimized to minimize biological effects on the nervous system, and more research is needed in this area. The present study is a regression analysis, and has detected small differences in slopes following a specific model for a typical Sternberg analysis. Future research will be made to confirm our results. Our results should be considered with caution, and longitudinal or follow-up studies are necessary (including wide demographic samples) to confirm them. There is also evidence in the literature that points towards a difference in the effects of MF exposures between men and women and this will be explored in our future research under current protocol.

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