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Human Cognitive Performance in a 3 mT Power-Line Frequency Magnetic Field

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Extremely low frequency (ELF, <300 Hz) magnetic fields (MF) have been reported to modulate cognitive performance in humans. However, little research exists with MF exposures comparable to the highest levels experienced in occupations like power line workers and industrial welders. This research aims to evaluate the impact of a 60 Hz, 3 mT MF on human cognitive performance. Ninety-nine participants completed the double-blind protocol, performing a selection of psychometric tests under two consecutive MF exposure conditions dictated by assignment to one of three groups (sham/sham, MF exposure/sham, or sham/MF exposure). Data were analyzed using a 3×2 mixed model analysis of variance. Performance between repetitions improved in 11 of 15 psychometric parameters (practice effect). A significant interaction effect on the digit span forward test ($F = 5.21$, $P < 0.05$) revealed an absence of practice effects for both exposure groups but not the control group. This memory test indicates MF-induced abolition of the improvement associated with practice. Overall, this study does not establish any clear MF effect on human cognition. It is speculated that an ELF MF may interfere with the neuropsychological processes responsible for this short-term learning effect supported by brain synaptic plasticity. Bioelectromagnetics 32:620–633, 2011. © 2011 Wiley Periodicals, Inc.

Key words: cognition; 60 Hz; extremely low frequency; performance

INTRODUCTION

Scientific literature shows evidence of biological and functional effects in humans exposed to extremely low frequency (ELF, <300 Hz) magnetic fields (MF); however, no widely accepted mechanisms have been identified [Cook et al., 1992, 2002; Crasson, 2003]. It is almost impossible to escape the presence of ELF MF in modern society. There are sources of naturally occurring ELF MF present on Earth. The prevalence of ELF MF in the environment is mainly from the use, distribution, and production of electric power. The World Health Organization (WHO) reports that the mean exposure in a European or North American home is <0.11 μT, and exposures can reach up to 400 μT near certain appliances [WHO, 2007]. The average exposure in European or North American office work is generally between 0.4 and 0.6 μT [WHO, 2007]. Occupations such as power line workers, welders, or electricians experience average exposures >3 μT [WHO, 2007]. Occupational exposures can reach up to 10 mT when working in close proximity to conductors carrying high currents [WHO, 2007]. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) have set guidelines for recommended maximum exposure levels. The 60 Hz levels of the IEEE are 904 μT for the general public and 2.71 mT for workers in a controlled environment

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[IEEE, 2002]. The new ICNIRP guidelines recommend (60 Hz) reference levels corresponding to a magnetic flux density of 200 μT for the general public and 1 mT for occupational exposures [ICNIRP, 2010]. These reference levels are calculated from basic restrictions expressed in terms of maximum allowed induced electric fields acceptable in biological tissue. These limits are established by applying a safety factor to the threshold for neural stimulation estimated in the human nervous system [IEEE, 2002; ICNIRP, 2010].

Various human biological systems have been examined, searching for indications of an interaction with MF and specific effects that have been reported on the cardiovascular, musculoskeletal, and central nervous systems. For instance, exposure to ELF MF has been found to alter heart rate and heart rate variability (indicative of an effect on heart rate control mechanisms) [Sait et al., 1999]. Electroencephalography (EEG) studies have found that ELF MF increase brain electrical activity in the alpha (8–13 Hz) wave range [Cook et al., 2002]. Studies have also found that human cognitive functions (attention and memory) are sensitive to MF exposure [Preece et al., 1998; Trimmel and Schweiger, 1998]. These findings are of interest to workers operating in environments with higher ELF MF levels than the general population (>500 μT for brief periods); does their environment increase the probability of cognitive error?

Human MF studies examining cognitive function have evaluated performance on a selection of psychometric tests in different power-line frequency MF environments (45–60 Hz; 20 μT to 1.26 mT). Typically, each test involves the measurement of a specific cognitive function such as working memory, perceptual reasoning, mental processing, long-term memory, or visuo-motor coordination. These functions are predominantly processed in the frontal lobes of the cortex [Cohen et al., 1996; Carpenter et al., 1999; MacLeod and MacDonald, 2000; Owen, 2000]. The performance of these cognitive functions is usually evaluated in terms of accuracy (correctness of response) and timing (speed of completion). Past results show that an ELF MF typically affects the accuracy, and rarely the timing, of a performed task [Preece et al., 1998]. Moreover, tasks with higher levels of difficulty seem to be more affected by the MF exposure. For example, Cook et al. [1992] observed a MF-induced effect illustrated by fewer errors with the choice reaction time task than with the simple reaction time task. The choice reaction time task was more challenging because the participant had to decide which of three buttons to press for a specific stimulus, while the participant only pushed a single button with the presentation of a stimulus for the simple reaction time task. Work conducted by Whittington et al. [1996] found that on the most difficult level of the visual duration discrimination task, performance was impaired during MF exposure. It should be noted that this study set $\alpha = 0.15$ to compensate for the low statistical power. A later study by the same group at Massey University (Palmerston North, New Zealand) observed an improvement in accuracy on the most difficult level of the visual duration discrimination task with the presence of the MF [Kazantzis et al., 1998]. Again, the alpha level was relaxed ($\alpha = 0.30$) to improve the statistical power. Both studies employed a 50 Hz, 100 μT MF with an exposure duration <10 min. The Massey University group's most recent article on ELF MF exposure and cognitive function indicates improvement in memory recognition after exposure but no change in the visual duration discrimination task [Podd et al., 2002]. This highlights another issue that has hampered ELF MF research—the inconsistency of replication.

A review article published by Crasson [2003] listed several possible reasons for the difficulty in reproducing results between and within laboratories. This includes differences in MF parameters such as exposure duration, field strength, frequency, interaction with the geomagnetic field, intermittent versus continuous exposure, order and time of day of exposure, orientation, polarity, waveform, and whole-body versus cephalic exposure. In addition, other differences found were studies with a low level of statistical power, inter-individual and inter-group differences, and variability in methodology, functional state of the nervous system, measurement parameters, and task difficulty. Given the inconsistent findings of work in this field, an Austrian group performed a meta-analysis on nine studies [Barth et al., 2010]. Significant effects were found with the visual duration discrimination task at the hardest level (exposed individuals showing better performance) and at the intermediate level (exposed individuals showing poorer performance). Barth et al. [2010] suggest treating the results with extreme caution due to the small number of studies per measurement parameter.

The most recent studies using sinusoidal 50 Hz MF (at 20, 100, or 400 μT) found no effects on working memory and cognitive flexibility [Delhez et al., 2004; Nevelsteen et al., 2007], selective and sustained attention tasks [Delhez et al., 2004; Crasson and Legros, 2005; Nevelsteen et al., 2007], and reaction time or time perception [Kurokawa et al., 2003; Delhez et al., 2004; Crasson and Legros, 2005]. However, a consistent effect appears to exist when the 50 Hz exposure level is >500 μT. Two studies show a reduction in cognitive performance on tests examining attention, perception, and memory. Preece et al. [1998] found that numerical working memory, delayed word recognition, and the choice reaction time accuracy all declined with exposure to a 50 Hz, 600 μT MF. There was no effect observed concerning speed in any of the tasks. At an even greater magnetic flux density (50 Hz, 1 mT) Trimmel and Schweiger [1998] found a reduction in performance on the amount of visual attention, precision of visual processing, speed and precision of perception, and verbal memory.

Higher MF exposure levels appear to be more effective at inducing a response in humans. Increasing the level of MF exposure at a fixed frequency will lead to higher induced fields and currents in exposed tissue, which are more likely to interact with synaptic processes and result in functional outcomes [ICNIRP, 2009]. A previous project from our group reported that a 60 Hz MF at 1.8 mT could modulate human standing balance control and physiological tremor [Legros et al., 2010], and brain activation patterns associated with a simple finger-tapping task [Legros et al., unpublished work].

The objective of the current research is to determine if exposure to a 60 Hz, 3 mT MF induces changes in cognitive performance (both correctness of response and speed of completion). Based on the literature reviewed, we hypothesize that exposure to 60 Hz, 3 mT MF will decrease the accuracy in test performance but will not affect the time participants take to carry out the task.

MATERIALS AND METHODS

Participants

Ninety-nine self-reported healthy volunteers (60 female, 39 male) participated in the study with a mean age of 23.5 years (range 18–49 years). The participants were recruited from a hospital (St. Joseph's Health Care, London, Ontario, Canada) and the university community (University of Western Ontario, London, Ontario, Canada) via poster advertisements. The University of Western Ontario Health Science Research Ethics Board approved the study (#13460) and all participants provided written informed consent. Exclusion criteria for participants in the study included: use of a hearing aid system; history of an epileptic seizure, or head or eye injury involving metal fragments; implanted electrical device (such as a cardiac or cerebral pacemaker) or intrauterine device; limitation of movement; metal braces on teeth or any permanent piercing; female participants who thought they may be pregnant or were actually pregnant; regular illicit drug use; and suffering from chronic illness (e.g., diabetes, psychiatric condition, or severe cardiovascular problems including susceptibility to arrhythmias or neurological diseases). Moreover, participants were asked to not smoke or consume caffeine or alcohol in the 12 h preceding their participation in the study.

Exposure Apparatus

The sinusoidal 60 Hz field was generated by two octagonal Helmholtz-like coils, 1.6 m wide and spaced 1.2 m apart (actual Helmholtz coils would be separated by half of their diameter, i.e., 0.8 m), positioned parallel to one another (Fig. 1). Each coil consisted of 158 turns of 10-gauge copper wire and was encased within plastic. Each encased coil was elevated 80 cm from the ground and held in position with a plastic frame. Non-electrically conductive high-temperature coolant tubing bordered the coils within the casing. The tubing was connected to two

Fig. 1. Participant performing one of the psychometric tests while seated between the two Helmholtz-like coils with the experimenter seated across.

refrigeration units (PolyScience, Niles, IL) that circulated an ethylene-glycol and water mixture to cool the coils. During the real exposure condition an electric current passed through the coils, which generated the 60 Hz, 3 mT (root mean square) MF (oriented ear-to-ear). The field was centered at the region of the participant's head and was homogeneous within ±5% for a 38 cm × 38 cm × 35 cm volume (Fig. 2; Table 1). The field strength was checked before each participant's experimental session to ensure it was properly calibrated. Each participant sat on a comfortable elevated chair located between the coils. A wooden table on a sliding track was positioned in front of the participant to carry out the testing. The experimenter sat across from the participant on the other side of the table (Fig. 1). The participant was fitted with ear plugs for the duration of both the baseline and experimental sessions. This made sure that the presence of the MF was not audible. Background vibration noise was recorded with a seismic accelerometer (Model 393A03, PCB Piezotronics, Depew, NY) placed between the coils. The background vibration was 1.80×10^{-2} m/s^2 with the MF off, compared to $2.08 \times 10^{-2} \pm 4.99 \times 10^{-5}$ m/s^2 when the MF was on. This difference is well below reported values for human linear acceleration detection thresholds [Kingma, 2005]. Thus, it is highly unlikely a participant would be aware of vibrations as a result of the field generation.

Procedure

Participants attended two sessions that were at least 1 day apart and started at the same time each day. The first session was a baseline session that lasted approximately 2.5 h. During this session, the participant completed the Oldfield Handedness Questionnaire [Oldfield, 1971], Beck Anxiety Inventory (BAI) [Beck and Steer, 1993], Beck Depression Inventory-II (BDI-II) [Beck et al., 1996], and the Wechsler Adult Intelligence Scale-III (WAIS-III) [Wechsler, 1997]. These are validated tests designed to evaluate the participants' handedness, as well as their levels of anxiety, depression, and intelligence. All tests were administered by a trained experimenter under the supervision of a clinical psychologist. If a participant endorsed a depression score (on the BDI-II) with an indication toward suicidal ideation, a protocol by the psychologist was put in place to intervene with the participant clinically and assist him or her in obtaining immediate medical attention. In addition, the Trail Making Tests A and B (TMTA and TMTB), Stroop, mental rotation (MR), and Fitts' Motor Task (FMT) were introduced in this session. The MF exposure was never generated during this session. Data collected from the BAI, BDI-II, and WAIS-III were used to confirm that the groups were homogeneous in terms of a psychological profile. The entire set of experimental psychometric tests

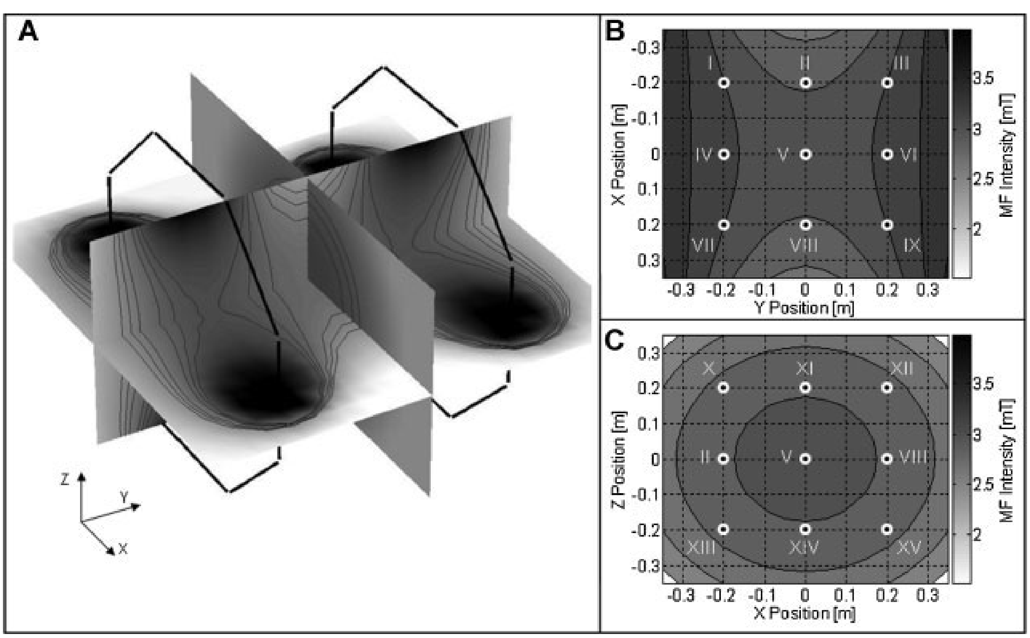

Fig. 2. **A**: Magnetic flux density in space around the two coils. The contour lines represent a 5% change in magnetic flux density. The middle region is 3 mT. **B**: Magnetic flux density in the sagittal plane. **C**: Magnetic flux density in the axial plane. (Actual measured field values given in Table 1.)

TABLE 1. Actual Measured Values of the Magnetic Field in Various Locations in Space

	Y-axis (Fig. 2B)			*Z*-axis (Fig. 2C)		
X-axis	−0.2 m	0.0 m	0.2 m	−0.2 m	0.0 m	0.2 m
0.2 m	I, 3.037 mT	II, 2.918 mT	III, 3.016 mT	X, 2.797 mT	XI, 2.894 mT	XII, 2.795 mT
0.0 m	IV, 3.086 mT	V, 2.993 mT	VI, 3.090 mT	II, 2.918 mT	V, 2.993 mT	VIII, 2.894 mT
−0.2 m	VII, 3.037 mT	VIII, 2.894 mT	IX, 3.067 mT	XIII, 2.817 mT	XIV, 2.877 mT	XV, 2.794 mT

was given during this session so the participant was familiar with them for the experimental session. The second session (i.e., the experimental session) lasted 2.5 h and consisted of a counterbalanced, double-blind, computer-driven protocol (LabView 8.5, National Instruments, Austin, TX) that included two testing blocks (referred to as B1 and B2, respectively) each preceded by a 30-min rest period. Prior to beginning session 2 the participant was randomly assigned to one of three experimental groups, which determined the order and presence of the MF exposure conditions (Fig. 3): Group 1 (sham/sham), Group 2 (real/sham), and Group 3 (sham/real). During a testing block, the participant completed the following subtests in order: Digit Symbol Coding (DSC), Block Design (BD), Arithmetic (AR), Digit Span Forward (DSF), Digit Span Backward (DSB), TMTA, TMTB, Stroop, MR, and FMT. At the conclusion of each test block, the participant completed the field status questionnaire to determine awareness of the MF exposure [Cook et al., 1992].

Measures

The performance of participants in each test was quantified during the different MF exposure conditions. The tests selected from the WAIS-III (DSC, BD, AR, DSF, and DSB) were modified from the original subtests of the WAIS-III to minimize the practice effects. The full WAIS-III was administered in the baseline session to establish the IQ score for each participant. Two alternate forms of the subtests were used to reduce the practice effects from same-day repeated measures testing. A detailed description and the characteristics of the tests used in this protocol are listed below.

Digit Symbol Coding. The DSC is a subtest that measures processing speed and visual motor coordination. Participants are presented with a page containing a key where the digits 1 through 9 are matched with a specific symbol. Below this are 133 digits with a blank space beneath each one. Each participant must copy the correct symbol into the blank spaces one after the other (without skipping any) as quickly and accurately as possible within a 90-s period. The score on the test is the number of squares filled in correctly [Wechsler, 1997].

Block Design. Participants are presented with designs and must use blocks (either four or nine, depending on design) with red and white markings to recreate these patterns. The answers are marked for correctness and speed of response, which will yield a score on the test [Wechsler, 1997]. Perceptual reasoning (spatial perception, visual abstract processing, and problem solving) and processing speed are associated with Block Designs.

Arithmetic. Participants listen to arithmetic questions, which are presented with increasing difficulty, and must solve them mentally (without the aid of pen, paper, or calculator). The number of correct answers within the allowable time frame produces the score [Wechsler, 1997]. Performance on this test reflects the participant's working memory and numerical reasoning.

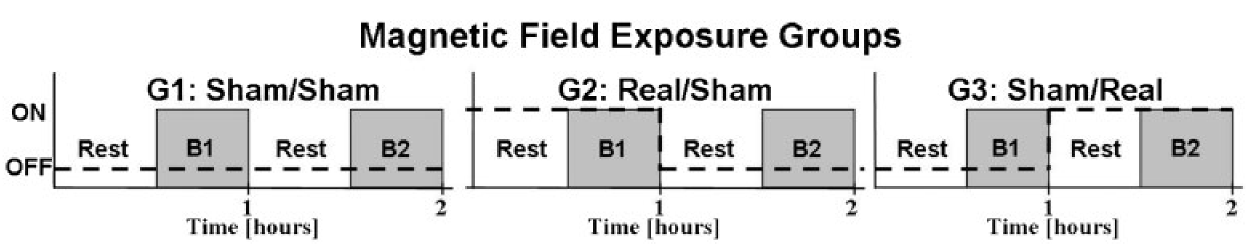

Fig. 3. Three MF exposure conditions: Group 1 (G1): sham/sham; Group 2 (G2): real/sham; Group 3 (G3): sham/real. B1 and B2 refer to the first and second test blocks, respectively. The broken line indicates the presence of the MF (on or off).

Digit Span Forward. The experimenter reads a sequence of digits to the participant who must repeat them back in the same order. After every second sequence the length increases by one. The parameter measured is the number of successfully repeated sequences out of 16, which are given as a score. This test evaluates working memory [Shum et al., 1990; Wechsler, 1997].

Digit Span Backward. This is similar to the DSF; however, after the experimenter reads a sequence of digits the participant must repeat them back in reverse order. The length of the sequence increases by one digit after every second trial sequence. The score is the number of successfully repeated sequences out of a maximum of 14. Like the DSF, this test evaluates working memory [Shum et al., 1990; Wechsler, 1997]. The DSB is considered more demanding than the DSF.

Trail Making Test, Part A. In the TMTA participants are presented with a sheet of paper containing the numbers 1–25 scattered about the page. Keeping their pencil on the paper, each participant must trace the numbers in ascending order as quickly and accurately as possible. The score is based on the time it takes to complete connecting the numbers 1–25. The test measures visual scanning, visual-motor coordination, and processing speed [Schear and Sato, 1989; Shum et al., 1990; Drane et al., 2002].

Trail Making Test, Part B. For the TMTB participants are presented with another paper that contains the numbers 1–12 and the letters A–L scattered about the page. Keeping their pencil on the paper, participants must trace the numbers followed by the letters in the pattern "1-A, 2-B, 3-C … 12-L." This is to be done as quickly and accurately as possible. Like the TMTA, the score is based on the time necessary to complete the trial. The test measures visual scanning, visual-motor coordination, processing speed, and cognitive set-shifting [Schear and Sato, 1989; Shum et al., 1990; LoSasso et al., 1998; Drane et al., 2002].

Stroop. To perform the Stroop test each participant interacts with custom designed software. On an LCD computer monitor, the participant is presented with a word printed in an ink color that is incongruent with the meaning of the word itself. Beneath the area where the word is presented are five buttons forming a pentagon (with a button at each of the five vertices). Each button has a color written on it (Blue, Brown, Green, Red, and Yellow) in black ink. The participant must use an optical mouse to move the cursor and click the button corresponding to the color of ink the presented word is printed in and not what the word is. This is to be done as quickly and accurately as possible. After each response, the mouse cursor is automatically moved to the center of the buttons on the screen. The percentage of correct responses and the mean time of responses are measured. This test examines processing speed, selective attention, and concentration performance [Stroop, 1935].

Mental Rotation. On the LCD computer monitor the participant is simultaneously presented with two images of 3D geometric objects. The participant must determine whether these are images of the same objects only rotated or if they are different (mirrored) objects. Like in the Stroop test, the participant uses an optical mouse to respond by either pressing a button (located beneath the display images) labeled "SAME" or "DIFFERENT." This is to be done as quickly and accurately as possible. After each click of the mouse, the cursor is returned to the starting position between the two response buttons on the screen. The percentage of correct responses and the mean time of responses are measured. This test evaluates perceptual reasoning (spatial perception and manipulation performance) and processing speed. The image pairs used in this test were taken from the original work of Shepard and Metzler [1971].

Fitts' Motor Task (FMT). The FMT requires the participant to move a stylus back and forth between two targets as quickly and accurately as possible. The stylus position is recorded with a Liberty 3D tracking system (Polhemus, Colchester, VT). The displacement from target 1 (the target closest to the dominant hand of the participant) and target 2, the mean time to move between targets, and the constant of proportionality are the analyzed parameters. The constant of proportionality (k) is calculated by:

$$k = \frac{t}{\log(2A/W)}$$

where t is the transit time to the target, A is the distance between the two target centers, and W is the mean displacement of the stylus tip from the target [Beuter et al., 1999]. The targets were spaced 0.30 m apart and were 0.005 m wide. The index of difficulty (I_d) is defined as: $I_d\,(\text{bits/response}) = -\log_2\left(\frac{W_s}{2A}\right)$ where W_s is the width of the target and A is the distance between targets [Fitts, 1954]. In this study the $I_d = 6.90$ bits/response. In Fitts' original work, the highest index of difficulty for the tapping task was 7 bits/response. This task is an indicator of processing speed and motor coordination.

Data Analysis

Statistics were performed using Predictive Analytics software (PASW 18.0, IBM, Somers, NY). The data collected during the baseline session with the BAI, BDI-II, and WAIS-III were analyzed with a one-way ANOVA testing for the group effect (to ensure the homogeneity of the three experimental groups). Each performance index collected in the experimental session was analyzed with a 3 (Group − between subjects factor) × 2 (Blocks − repeated measure) mixed-model ANOVA. The *F*-ratio (F), *P*-value (*P*), and partial eta-squared (η_p^2) for each performance index is reported. The η_p^2 (also called estimated effect size) is the proportion of variance attributable to the effect.

RESULTS

Homogeneity of Groups

The one-way ANOVA was conducted to demonstrate that there were no differences among the three groups in terms of anxiety, depression, and intelligence. As expected, in the baseline session there were no significant differences between the three groups (Table 2) for scores on the BAI ($F = 0.16$, $P > 0.05$), BDI-II ($F = 0.64$, $P > 0.05$), and WAIS-III ($F = 0.32$, $P > 0.05$). All groups scored the same on levels of anxiety (none to minimal), depression (none to minimal), and intelligence (above average).

Field Status Questionnaire

The χ^2 analysis of participants' responses to the field status questionnaire (given at the end of each experimental block) revealed participants were not able to judge the presence of the MF at better than chance levels (54.1% correct; $\chi^2 = 1.49$, degrees of freedom (df) 1, $P > 0.05$, Yates correction applied). Participants did not accurately report that they were able to hear or "feel" the MF.

Main Analysis

The 3 (Group) × 2 (Blocks) ANOVA was conducted on each performance index in order to test for differences between Groups (Table 3) and/or Blocks (Table 4), as well as any interaction between the Group and Block factors (Table 5). Results did not show any significant group effects for any of the psychometric measures (Table 3). The performance on the tests, averaged over both blocks in the experimental session, is not considered different for all three groups. However, a significant block effect was found for several performance indexes (Table 4). The scores on the DSC, BD, DSF, DSB, and Stroop percent of correct responses (accuracy), and mean displacement from target 2 on the FMT were increased in Block 2 compared to Block 1. The performance, in terms of completion time (score) and accuracy, improved with repetition of these tests. In contrast, the mean completion time of the TMTA, Stroop, MR, and FMT, as well as the constant of proportionality on the FMT, were decreased in Block 2 compared to Block 1. The time necessary to complete tasks is reduced after repetition during the experimental session. The AR score, TMTB time, MR percent of correct responses (accuracy), and the mean displacement from target 1 on the FMT did not differ between Block 1 and Block 2. Overall, participant performance did not change as these tests were repeated.

Interestingly, results pointed toward a significant interaction for the DSF test ($F = 5.21$, $P < 0.05$; Table 5). In Group 1 (control group, no applied MF) the score in Block 2 was greater than Block 1, but in Group 2 and Group 3 (exposure groups) the scores for Block 1 and Block 2 were not different (Fig. 4). This indicates an improvement in the number of digits remembered with no MF exposure and no improvement when the MF is present in either experimental block.

DISCUSSION

This study used a double-blind, counterbalanced procedure to evaluate the impact of a 60 Hz, 3 mT MF on selected cognitive functions. The functions selected were investigated in previous studies examining effects of MF and other environmental stimuli (such as lead and manganese) on cognition [Otto et al., 1992; Hanninen et al., 1998; Beuter et al., 1999; Delhez et al., 2004; Bowler et al., 2006;

TABLE 2. Baseline Scores for BDI-II, BAI, and WAIS-III Presented as the Mean ± Standard Error of the Mean

Group (#male/#female)	Mean age	BAI	BDI-II	WAIS-III
Group 1 (14/19)	23.2 ± 7.0	4.2 ± 0.8	4.2 ± 0.8	111 ± 1.7
Group 2 (14/19)	23.7 ± 5.1	4.4 ± 1.0	5.4 ± 0.9	110 ± 2.0
Group 3 (11/22)	23.6 ± 6.8	3.7 ± 0.6	4.6 ± 0.7	110 ± 1.8

TABLE 3. Block 1 and Block 2 Mean Values for Each Group and Group Effect Statistics

Measurement parameter	Group 1	Group 2	Group 3	F	P	η_p^2
Digit symbol coding						
Score	63.47 ± 1.87	60.13 ± 2.05	61.46 ± 2.02	0.74	0.48	0.02
Block design						
Score	51.86 ± 1.09	51.10 ± 1.44	52.43 ± 0.83	0.18	0.84	0.00
Arithmetic						
Score	8.12 ± 0.30	7.68 ± 0.33	8.24 ± 0.28	1.68	0.19	0.03
Digit span forward						
Score	11.88 ± 0.44	11.63 ± 0.40	11.93 ± 0.41	0.22	0.80	0.01
Digit span backward						
Score	8.48 ± 0.46	8.21 ± 0.39	8.68 ± 0.41	0.48	0.62	0.01
Trail making, part A						
Time (s)	23.59 ± 1.25	22.44 ± 1.25	25.15 ± 1.24	0.26	0.78	0.01
Trail making, part B						
Time (s)	43.33 ± 3.37	45.56 ± 3.59	43.55 ± 2.19	0.93	0.40	0.02
Stroop						
Percent accuracy	98.03 ± 0.37	98.87 ± 0.23	98.41 ± 0.33	1.77	0.18	0.04
Response time (s)	1.41 ± 0.03	1.43 ± 0.05	1.40 ± 0.03	0.45	0.64	0.01
Mental rotation						
Percent accuracy	84.52 ± 2.50	83.51 ± 2.14	81.31 ± 2.52	0.56	0.57	0.01
Response time (s)	5.77 ± 0.35	6.58 ± 0.40	5.70 ± 0.37	1.52	0.22	0.03
Fitts' motor task						
Target 1 displacement (cm)	0.45 ± 0.03	0.53 ± 0.05	0.50 ± 0.03	1.58	0.21	0.03
Target 2 displacement (cm)	0.35 ± 0.03	0.41 ± 0.03	0.38 ± 0.03	1.38	0.26	0.03
Movement time (s)	0.67 ± 0.03	0.63 ± 0.03	0.64 ± 0.03	0.52	0.60	0.01
Constant of proportionality	0.25 ± 0.01	0.25 ± 0.01	0.25 ± 0.01	0.18	0.83	0.00

TABLE 4. Mean Comparison Across All Groups for Block 1 and Block 2 for All Measurement Parameters

Measurement parameter	Block 1	Block 2	F	P	η_p^2
Digit symbol coding					
Score	60.29 ± 1.15	63.05 ± 1.13	19.90	0.00*	0.17
Block design					
Score	50.50 ± 0.72	53.09 ± 0.60	38.87	0.00*	0.29
Arithmetic					
Score	7.85 ± 0.19	8.17 ± 0.16	3.91	0.06	0.04
Digit span forward					
Score	11.62 ± 0.24	12.00 ± 0.25	4.53	0.04*	0.05
Digit span backward					
Score	8.14 ± 0.22	8.74 ± 0.26	8.46	0.01*	0.08
Trail making, part A					
Time (s)	24.32 ± 0.74	21.39 ± 0.66	24.29	0.00*	0.20
Trail making, part B					
Time (s)	45.65 ± 2.06	42.66 ± 1.53	4.40	0.09	0.40
Stroop					
Percent accuracy	97.94 ± 0.90	98.13 ± 0.27	6.34	0.01*	0.06
Response time (s)	1.48 ± 0.02	1.37 ± 0.02	32.54	0.00*	0.25
Mental rotation					
Percent accuracy	82.21 ± 1.49	84.06 ± 0.06	2.35	0.13	0.02
Response time (s)	6.55 ± 0.26	5.49 ± 0.18	39.59	0.00*	0.29
Fitts' motor task					
Target 1 displacement (cm)	0.49 ± 0.02	0.50 ± 0.02	0.86	0.36	0.01
Target 2 displacement (cm)	0.36 ± 0.02	0.40 ± 0.02	16.33	0.00*	0.14
Movement time (s)	0.66 ± 0.02	0.62 ± 0.02	42.77	0.00*	0.31
Constant of proportionality	0.26 ± 0.01	0.25 ± 0.01	22.14	0.00*	0.19

*Significant result at $P < 0.05$.

TABLE 5. Interaction Effect Statistics of All Measurement Parameters

Measurement parameter	*F*	*P*	η_p^2
Digit symbol coding			
Score	0.56	0.58	0.01
Block design			
Score	0.67	0.51	0.01
Arithmetic			
Score	1.34	0.27	0.03
Digit span forward			
Score	5.21	0.01*	0.10
Digit span backward			
Score	2.12	0.13	0.04
Trail making, part A			
Time (s)	0.05	0.95	0.00
Trail making, part B			
Time (s)	0.38	0.69	0.01
Stroop			
Percent accuracy	0.11	0.90	0.00
Response time (s)	2.20	0.12	0.04
Mental rotation			
Percent accuracy	1.80	0.17	0.04
Response time (s)	0.41	0.66	0.01
Fitts' motor task			
Target 1 displacement (cm)	1.63	0.20	0.03
Target 2 displacement (cm)	0.32	0.73	0.01
Movement time (s)	1.10	0.34	0.02
Constant of proportionality	0.14	0.87	0.00

*Significant result at $P < 0.05$.

Counter et al., 2009]. Cognitive functions were assessed by testing human volunteers distributed into three experimental groups that were shown to be homogeneous in terms of the levels of anxiety, depression, and intelligence. For each group, the mean BAI score corresponded to the lowest anxiety level (score 0–7) [Beck and Steer, 1993] and the mean BDI-II score was in the lowest depression interval (score 0–13) [Beck et al., 1996]. Though the mean score for Group 2 is higher than Group 1 and Group 3, this does not suggest the groups are at different levels of depression. The scoring scale of the BDI-II is 0–63 and the difference between scoring (4 vs. 5) on the BDI-II is not particularly notable. This was an important result since increased levels of anxiety and depression are shown to negatively impact cognitive function [Purcell et al., 1997; Grant et al., 2001; Coles and Heimberg, 2002; Porter et al., 2003]. These scores eliminate anxiety and depression as possible confounds. All groups had mean IQ scores in the higher than average intelligence range (score 100–115) [Wechsler, 1997]. This is expected because the majority of the study population consisted of university students.

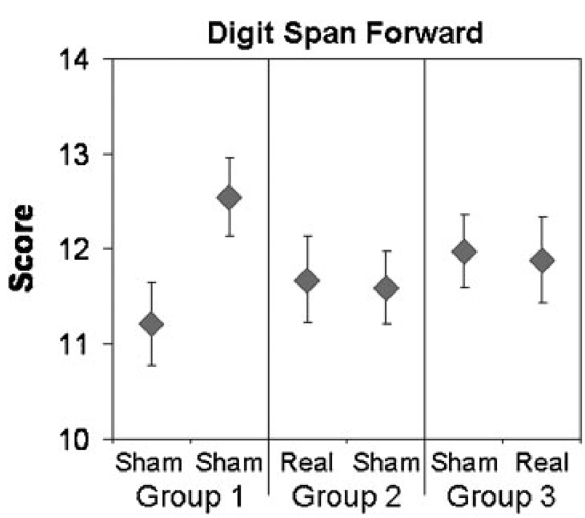

Fig. 4. Digit span forward mean scores obtained in each experimental condition (real or sham), displayed by group. The error bars represent one standard error of the mean. Note that there is an increase in performance with repetition for Group 1 (control group) but no increase with repetition for either of the exposure groups (Group 2 and Group 3).

The participants did not detect the presence or absence of the MF. This is a very satisfying result considering the high level of MF exposure (per a recent review of the literature, 3 mT is the highest level reported in ELF MF human cognitive studies published in a peer-reviewed journal). The highest magnetic flux density found in previous ELF MF studies involving cognitive testing was 1.26 mT [Lyskov et al., 1993a,b]. However, it is important to take the orientation of the field into account since different MF orientations would also lead to different induced current orientations. This information was not always reported in past studies and is one of the possible reasons for differences between cognitive results. In this particular case, Lyskov et al. [1993a, b] used a MF oriented "ear-to-ear."

The block effect present for many of the tests suggests a practice effect. The practice effect is an improvement in neuropsychological performance attributable to the effects of repeated assessment with the same instrument [McCaffrey and Westervelt, 1995]. The presence of practice effects is expected to assess changes in cognitive ability with repeated measures testing. Unfortunately, "there are relatively few cognitive tests designed explicitly for the repeat assessment of cognitive function" [Wilson et al., 2000]. A commonly used strategy to cope with this is administering alternate forms of assessments to reduce the practice effects that accompany repeated measures testing [Desrosiers and Kavanagh, 1987; Kelland and Lewis, 1994; Benedict and Zgaljardic, 1998; Beglinger et al., 2005]. Two alternate versions of the experimental session tests are implemented in this study. However, alternate forms of assessments do not eliminate practice effects [Uchiyama et al., 1995; Dikmen et al., 1999]. Another factor contributing to practice effects is the above-average intelligence of the participants. It is reported that people with average or high average IQs on initial testing are more likely to make improvements on repeated testing than people with low average IQs [Rapport et al., 1997]. The presence of the practice effect in this study grants the opportunity to not only evaluate the effect of MF exposure on cognitive performance but also on the practice effect. Practice is proven to change brain activation patterns in imaging studies [Kelly et al., 2006; Ischebeck et al., 2007; Jolles et al., 2010]. A decrease in activation due to practice is suggested to be the result of increased neural efficiency with less neurons in a neural network firing in response to a task or stimulus [Garavan et al., 2000; Poldrack, 2000; Duncan and Miller, 2002]. There are also practice-related increases in brain activation. The increases are attributed to additional neurons firing in a particular region of the brain, indicating a strengthened response [Poldrack, 2000]. Generally, decreases in activation are associated with practice on cognitive tasks while increases are associated with practice on sensory or motor tasks [Kelly et al., 2006]. The ability of the human brain to alter the number of neurons and neuronal firing patterns associated with tasks in response to experiences is referred to as neural plasticity [Kelly et al., 2006].

The tests accounting for cognitive set-shifting (TMTB), processing speed (BD, TMTA, MR, and FMT), visual-motor coordination (DSC, TMTA, and TMTB), and visual scanning (TMTA and TMTB) improved performance with repetition independently of the MF exposure condition. This practice effect has been documented in previous research using the aforementioned tests [Fitts, 1954; Wexler et al., 1998; Fastenau et al., 2001; Bird et al., 2004; Hinton-Bayre and Geffen, 2005; Miller et al., 2009; Solana et al., 2010]. These tests are associated with the prefrontal cortex [Shibuya-Tayoshi et al., 2007], precentral gyrus, cingulate gyrus, medial frontal gyrus [Zakzanis et al., 2005], left middle frontal gyrus, and posterior parietal cortex [Usui et al., 2009]. Within the brain this practice effect would likely reflect an increase in neural efficiency in the prefrontal cortex, cingulate gyrus, medial frontal gyrus and middle frontal gyrus, and an increase in neural firing in the precentral gyrus and posterior parietal cortex (regions associated with motor activity).

Verbal working memory showed an improvement from Block 1 to Block 2 on the digit span tasks. This is consistent with the literature, which has shown practice effects to be present [Taub, 1973; Otto et al., 1992; Dikmen et al., 1999; Wilson et al., 2000; Farahat et al., 2003]. The orbitofrontal and mid-ventrolateral frontal cortex are very prominent in neuroanatomical studies using digit span tasks [Owen, 2000]. It is likely that the associated neural pathways increase efficiency as the test is repeated.

The processing speed of perceptual reasoning and mental imagery increased between repetitions, which is in agreement with the findings of other studies [Vandenberg and Kuse, 1978; Wexler et al., 1998; Miller et al., 2009]. The BD and MR tests are associated with spatial processing in the dorsal occipital-parietal pathway [Booth et al., 2000; Koshino et al., 2005], motor cortical areas [Kosslyn et al., 1998; Jordan et al., 2001], and demands on executive functions in the prefrontal regions [Cohen et al., 1996; Carpenter et al., 1999]. The practice effect indicates that a change in neural patterns could be occurring in one or more of these areas.

Also consistent with the findings of previous research, the concentration task performance (Stroop) improved from Block 1 to Block 2 [Davidson et al., 2003; Beglinger et al., 2005]. Two areas of the brain thought to have a key role in concentration are the dorsolateral prefrontal and anterior cingulate cortex [MacLeod and MacDonald, 2000]. Since concentration is a cognitive task (as opposed to sensory or motor task) the improvement between blocks is likely the result of improved efficiency of neuron firing in these regions with task repetition.

The participants' overall performance on the motor task improved over time as indicated by the lowering of the constant of proportionality. This constant is a measure of inherent ability, independent of the speed/precision trade-off when performing the task [Beuter et al., 1999]. There was an increase in displacement from target 2 (the farthest from the dominant hand of the participant) between Block 1 and Block 2. It was coupled with a decrease in the time taken to move between targets, suggesting a decrease in precision due to a rise in speed and confidence. In Fitts' original work, participants improved their speed (by 3%) between the first and second trials but did not make more errors [Fitts, 1954]. The improvement in our study was 6% but with a decrease in the precision of tapping, which could be caused by the increase in speed. Since this is a motor task, it is expected that the practice effect indicates an increase of neural firing in the associated neural pathway.

The only interaction effect present is for the DSF memory task, which suggests a MF-induced effect. This interaction does not equate to a change in test accuracy because of MF exposure but rather an elimination of the practice effect. Both of the exposed groups did not experience an improvement with repetition. However, the control group improved test performance after a repeated administration of the DSF as regularly reported in the literature [Taub, 1973; Otto et al., 1992; Subramanya and Telles, 2009]. In fact, it is even more likely that a practice effect would be present on this test because of the short test–retest interval [Benedict and Zgaljardic, 1998]. A recent functional magnetic resonance imaging (fMRI) study found changes in brain activation in regions of the prefrontal cortex on working memory tests with repetition [Jolles et al., 2010]. Owen [2000] found a verbal DSF task (like the one used in this study) activated the orbitofrontal and mid-ventrolateral frontal cortex of the human brain. Under control group conditions it is expected that neurons in these regions would operate more efficiently as the task is repeated. Therefore, it is possible that the MF will interfere with the neurophysiological processes underlying the plastic adaptation of neural pathways in these regions.

It is unexpected that both DSF and DSB did not show similar interactions because both tasks demonstrated activation in the same brain regions (orbitofrontal and mid-ventrolateral frontal cortex) except for the mid-dorsolateral frontal cortex (DSB only) [Owen, 2000]. However, it has been suggested that DSF and DSB involve various cognitive processes, which may be differently impaired in certain clinical groups [Kaplan et al., 1991; Lezak, 2004]. In addition, it may be possible that in the DSB, the mid-dorsolateral frontal cortex is compensating for the impairment in the neural pathways of the orbitofrontal or mid-ventrolateral frontal cortex demonstrated in DSF.

This would not be the first ELF MF study to report an alteration of the practice effect. Another study on cognitive functions reported an attenuation of practice effects on reaction time with exposure. The groups receiving sham first performed better on the reaction time task during the second trial than groups receiving the real exposure first [Lyskov et al., 1993a,b]. The exposure level in these findings was the previous highest level reported in ELF MF research on human cognitive function (1.26 mT).

Since the number of males and females in each group was not perfectly balanced, we tested for a gender effect. We found that there were gender effects present but only for the score of the AR test and the MR percent of correct responses. Males performed better than females on both tests. Gender differences on AR and MR tests have been well documented in psychometric literature [Voyer et al., 1995; Lynn and Irwing, 2008]. Separating the three experimental groups into males and females for the AR and MR tests did not reveal any MF-related effects. Although AR is a working memory test, it is important to emphasize that there were no gender effects for DSF and DSB. This agrees with past research, demonstrating a lack of gender effects for digit span tests [Lynn and Irwing, 2008]. Therefore, it is unlikely that the significant DSF result is influenced by gender differences.

It is possible that the significant DSF result could be influenced by group-specific differences. However, that is very unlikely since age and intelligence (two major factors contributing to the practice effect) are similar for all groups. A visual examination of Figure 4 may suggest a difference between the Block 1 DSF scores for Group 1 and Group 3. We would like to emphasize that our statistical results do not support this observation. A *t*-test comparing the Block 1 DSF scores for Group 1 and Group 3 revealed no significant difference.

To gain a better understanding of the changes within the brain because of MF exposure, future studies should utilize EEG and fMRI. Imaging with fMRI would present excellent spatial resolution in determining exactly which parts of the brain are being affected. Future studies should also focus on the orbitofrontal and mid-ventrolateral frontal cortex structures of the brain because these results suggest that they may be affected by the MF exposure.

CONCLUSION

Our results agree with the hypothesis that the MF exposure would not have an effect on participant processing speed. However, exposure to a 60 Hz, 3 mT MF did not alter the accuracy of human performance on the DSC, BD, AR, DSF, DSB, Stroop, MR, and FMT. There is the possibility that the MF exposure could modulate the normal practice effect of a memory task. Future studies should utilize complementary assessment tools like the EEG and fMRI for further insight into MF interaction with human cognitive processing. The lack of well-defined and reliable cognitive effects in terms of accuracy and processing speed at this exposure level should be noted by organizations developing guidelines. In the future, experimental magnetic flux density exposure should be increased until a threshold for an effect is found and the mechanism responsible is identified.

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