FUNCTIONAL MAGNETIC RESONANCE IMAGING OF THE EFFECTS OF A 60 HZ MAGNETIC FIELD ON HUMAN CORTICAL ACTIVITY DURING A MENTAL ROTATION TASK

JODI MILLER
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

JULIEN MODOLO
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

JOHN ROBERTSON
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

MICHAEL CORBACIO
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

DANIEL GOULET
HYDRO-QUÉBEC
800 BOULEVARD DE MAISONNEUVE EST - 21E ÉTAGE, MONTRÉAL, QUÉBEC,
H2L 4M8, CANADA

JACQUES LAMBROZO
SERVICE DES ÉTUDES MÉDICALES, EDF
22-28 RUE JOUBERT, PARIS, 75009, FRANCE

MICHEL PLANTE
HYDRO-QUÉBEC

MARTINE SOUQUES
SERVICE DES ÉTUDES MÉDICALES, EDF
22-28 RUE JOUBERT, PARIS, 75009, FRANCE

FRANK S. PRATO
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

ALEX W. THOMAS
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

ALEXANDRE LEGROS
LAWSON HEALTH RESEARCH INSTITUTE, UNIVERSITY OF WESTERN ONTARIO
268 GROSVENOR STREET, LONDON, ONTARIO, N6A 4V2, CANADA

Abstract

It has previously been demonstrated that Extremely Low Frequency (ELF) magnetic fields (MF) can modulate human neurophysiology. In this study Functional Magnetic Resonance Imaging (fMRI) was used to determine the effect of exposure to an ELF MF on brain regions involved in a mental rotation task.

For this task each subject was asked to compare two 3-dimensional objects which were either identical or mirror images, rotated by a certain amount of degrees in the x and y direction. Subjects had to determine if these objects were the same or different. Upon completion of this task subjects were either exposed to a 60 minute 60 Hz, 3000 μT MF or to a 60 minute sham condition, after which they completed a post-exposure mental rotation task. Functional images were analyzed to determine if there were any differences between pre- and post-exposure brain activation using BrainVoyager QX2.0.8.1480.

Significant interactions were found between sham and real exposure groups between the pre- and post-exposure activation in the intraparietal sulcus and Brodmann Area 19, regions associated with visual attention and visual processing. There was post-exposure activation in Brodmann Area 19 in the sham group as compared to the real exposure group was significant (($F= 7.426$, $p < 0.05$, df = 1, 7). A post-exposure decrease in activation in the intraparietal sulcus was associated with MF exposure in the real exposure group ($F = 6.676$, $p < 0.05$, df = 1, 7).

These results demonstrate that a 60-minute exposure to an ELF MF may affect visual attention and visual processing during the mental rotation task. Furthermore, fMRI shows promise as a valuable tool for observing the effects of ELF MF exposure on certain brain processes such as those associated with a mental rotation task.

Introduction

The Institute of Electrical and Electronics Engineers (IEEE) has recommended a maximum level for human magnetic field exposure of 2700 μT at 60 Hz, the power line frequency in North America (IEEE, P1555/D5, (2001)). Previous studies of the effect of human exposure to magnetic fields have demonstrated that Extremely Low Frequency (ELF, < 300 Hz) Magnetic Fields (MF) can modulate human neurophysiology, including cognitive functions (for a review, see Cook et al., 2002; Preece et al., 1998).

These studies measured the effect of a 50-60 Hz weak magnetic field on memory, attention and information processing using cognitive testing performance measures and found inconsistent results (Crasson, 2003). Those that had significant findings found small changes that have been difficult to reproduce (Crasson, 2003). For example, Preece et al. (1998) observed a temporary deterioration in attention, working and secondary memory performance with the application of a 50 Hz field. Another study by Kurokawa et al. (2003) observed the effects of a short-term exposure to 50 Hz magnetic fields on cognitive performance function in humans and found that the field had no significant influence on reaction time, time and accuracy of choice reaction, time perception and figure perception. Podd et al., (2002) were unable to find any effects of a 50 Hz field on reaction time and accuracy in a visual discrimination task, but observed a delayed effect on memory.

With the advent of functional magnetic resonance imaging (fMRI), it is possible to identify brain regions, which are activated during a particular functional task (Ogawa et al., 1990). The mental rotation task (Shepard & Metzler, (1971)) is used extensively in cognitive sciences to measure a person's ability to manipulate spatial information. Researchers have been able to identify specific brain regions activated during this task (Cohen et al., 1996) using fMRI. These studies have consistently observed a response in regions involved in visual processing, the integration of visual and motor information, executive function and cognitive control (Cohen et al., 1996); Richter et al. 2000; Vingerhoets et al. 2002; Wexler et al. 1998; Windischberger et al. 2003). In addition, it has recently been demonstrated that fMRI has the ability to measure the effect of ELF MF on neuroprocessing (Robertson et al., 2010).

This work has investigated the effects of a 60 minute, 60 Hz, 3000 μT MF exposure on brain activation during: 1) rest; 2) a tapping task; and 3) a mental rotation task with a focus on the mental rotation task. To date, no published studies have specifically observed the effect of ELF MF on the mental rotation task.

Hypothesis

We hypothesize that exposure to ELF MF can alter cognitive performances (Cook et al., 2002), and that functional brain activation associated with a mental rotation task will be modulated by a 60-minute 60 Hz, 3000 μT MF exposure.

Methods

Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging is a technique, which maps changes in brain blood flow corresponding to brain activation (Ogawa et al., 1990). This technique is possible because of the blood oxygenation level dependent (BOLD) signal, which is the contrast between high signal oxygenated hemoglobin in blood and low signal deoxygenated hemoglobin in blood. When performing a task, a change in neural activity causes oxygenated blood to flow to the activated brain region. A block design (task vs. rest) is used to acquire sets of brain images during the BOLD-fMRI sequence. Blood flow during the task is compared to blood flow during rest. For this study, fMRI analysis requires a correlation of the signal change over time for each image pixel with either the mental rotation task or rest. This task-related activation was then compared pre- and post-exposure for the real and sham exposure groups.

The mental rotation task

In this task subjects are presented with two 3-dimensional objects, which are projected side-by-side on a screen (Figure 1). Participants are asked to compare the objects and determine, as fast as they can, if these are the same objects rotated by either 0°, 30°, 60° or 90° or mirror images of each other rotated by the same number of degrees. The purpose of this task is to determine both the rate of spatial processing and intelligence (Johnson 1990; Jones and Anuza, 1982). Subjects are rated on speed and how accurately they can distinguish between the mirrored and non-mirrored images. Using fMRI, brain regions consistently associated with the mental rotation task have been identified as Brodmann Areas 7A and 7B, the middle frontal gyrus, extra-striate cortex, the hand somatosensory cortex and frontal cortex (Cohen et al., 1996).

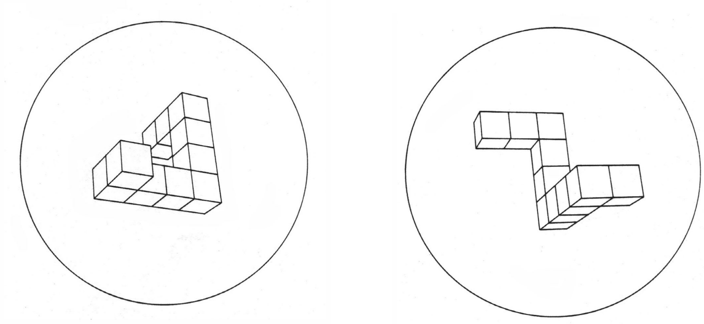

Figure 1. Object images from the mental rotation task. The same object has been rotated by 60º.

In this study, the two object images were projected onto a screen located at the foot of the MRI patient bed. BOLD functional images were produced by the comparison of the task vs. rest conditions, which were presented in alternating 15-second blocks. During the task subjects used an MRI compatible button press to indicate if the objects were the same or different and during the rest period blank white boxes were displayed on the screen. LabView (National Instruments, USA) software was used to present the images and to record the button press data. This task was given before and after a 60-minute rest period that may or may not have involved 60 Hz MF exposure (Figure 2).

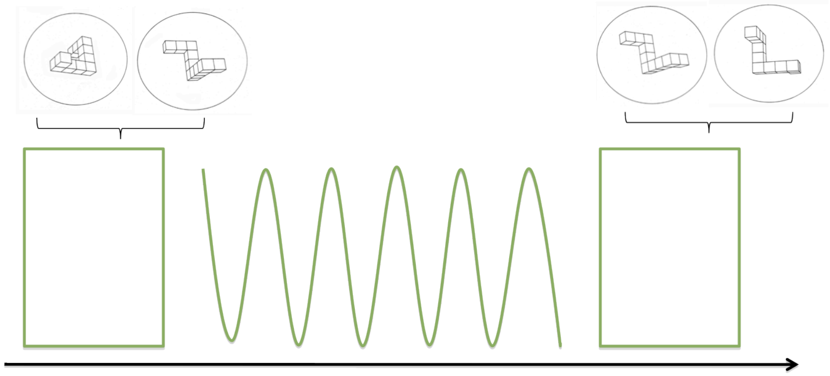

Figure 2. : BOLD images were acquired while participants performed the mental rotation task (for a duration of 5 minutes and 30 seconds) before and after a 60 minute exposure to a 3000 µT MF at 60 Hz. In the sham group the 60 Hz MF was not presented during the 60-minute rest period.

Subjects

Nine healthy right-handed subjects (age = 23 ± 4; 6 females, 3 males) were recruited from the university community. Informed written consent was obtained from all subjects before each scan, according to the guidelines of the University of Western Ontario Health Sciences Research Ethics Board (#119565E). Exclusion criteria for subjects included a history of serious medical illness, drug or alcohol abuse, history of head or eye injury involving metal fragments or any magnetic/electrical implants. A standard MRI screening questionnaire was given to participants prior to the experiment to ensure their safety in the MRI. Subjects were not permitted to have caffeine, nicotine, or alcoholic beverages 24 hours before the study and were randomly assigned to one of two groups: 1) real exposure to the extremely low frequency magnetic field (n = 5) or 2) sham exposure (n = 4) in a pseudo double-blind procedure.

Experiment

All subjects completed the Oldfield handedness questionnaire (Oldfield, 1971) to determine their hand dominance prior to participation in the study. Functional MRI data was acquired during a 2 hour session in a 3.0 Tesla research magnetic resonance imaging scanner (Siemens/Verio Erlangen, Germany). Subjects were placed in the magnet supine and their heads were restrained within a 32 channel phased array head coil with foam padding to ensure minimal movement during the scan. Each MRI session began with the acquisition of a structural T1 weighted anatomical image for fMRI data registration (MP-RAGE (magnetization prepared radio-frequency pulse and rapid gradient-echo sequence, TR = 1900 ms, matrix = 256 x 256, 176 slices, 1 mm isovoxel). Subjects then completed 3 pre-exposure tasks: 1) resting blood flow; 2) tapping task; and 3) the mental rotation task. The mental rotation task BOLD-fMRI data (115 volumes) was acquired using an echo planar imaging (EPI) sequence (5 minutes and 45 seconds, TR = 3000 ms, TE = 30 ms, 500 ms delay; matrix = 64 x 64; 3 mm slice thickness, 1.25 mm gap; flip angle = 90°).

Subjects then underwent a 60-minute rest period within the magnet, during which the participant was either exposed to a 60 Hz, 3000 µT MF or the sham condition. Our MRI physicist (Dr. Théberge) programmed the gradient coil of the MRI to create the 60 Hz, 3000 µT sinusoidal MF. The field exposure was produced using the Z gradient coil, where the greatest intensity of the time-varying MF was at the top of the cortex (1 cm below the top of the skull) and a linear gradient to the null point at isocentre (first cervical vertebrae). As the zero field is located at the isocentre of the magnet bore, the subject was moved further into the magnet to ensure the entire brain was exposed to the 60 Hz MF. An audio clip mimicking the sound of the ELF MF was played for the sham group during this period and the subjects were moved to the same position within the magnet as the real exposure group to ensure a similar auditory and physical environment for both groups during the rest period. Both groups completed the 3 tasks post-exposure to determine the effect of the 60 Hz MF exposure on brain activation for each task. Upon completion of the study, participants completed the Field Status Questionnaire (FSQ) (Cook et al., 1992) to determine if the subjects were aware of their exposure condition.

Analysis

Regions of interest (ROI) from the fMRI acquisition were chosen using *a priori* information of the brain regions associated with the mental rotation task (Cohen et al., 1996). The data was processed with BrainVoyager (QX 1.9.10, Brain Innovation, The Netherlands). Functional data were pre-processed using 3D motion correction and temporal filtering to remove head movement and signal drift. A 3D Gaussian smoothing kernel of 8 mm FWHM was applied for spatial smoothing to improve registration across participants. Functional images were co-registered to the T1 weighted anatomical image and were then normalized to Talairach space. The statistical analysis was completed in BrainVoyager using a multi-study general linear model (GLM) analysis with a p value of $p < 0.001$.

Pre-exposure activation maps were produced for all subjects to determine if the study replicated previous fMRI studies of the mental rotation task. Post- minus -pre- exposure images were produced for each of the sham and real conditions. Beta weights were extracted from each ROI. The beta weights for each ROI was analyzed separately using PASW Statistics 18 Release 18.0.0, where a repeated measures ANOVA with a between-subjects factor (exposure group) was conducted. For this study $p < 0.05$ was considered significant and was reported as a non-significant trend when $0.05 \leq p \leq 0.1$.

The button press data for the mental rotation task was analyzed using Matlab (Mathworks, USA) to determine the speed and accuracy of the subjects' responses. A repeated measures ANOVA (within subjects: time; between subjects: condition) was then applied to determine if there were significant differences in speed and accuracy before and after the rest period for both the real and sham exposure group.

A Chi-squared test was applied to the FSQ results for each of the sham exposed and the exposed group.

Results

The pre-exposure (real + sham, n = 9) activation maps of the mental rotation task uncovered activation in regions associated with the integration of visual and motor information, visual processing and executive function and cognitive control; which are all regions that have been linked with the mental rotation task in previous fMRI studies (Cohen et al., 1996). The multi-study GLM analysis in BrainVoyager uncovered a significant decrease in activation in the real exposure group in the left intraparietal sulcus, a region associated with visual attention after exposure. A multi-study GLM analysis of Brodmann Area 19, a region associated with visual processing in the occipital lobe, uncovered a significant increase in activation in the sham exposure group within this region.

Results from the FSQ showed that all subjects in both exposure groups could not determine whether or not they were in the real exposure group or the sham exposure group (FSQ: $\chi^2 = 1.718$, $p > 0.05$; level of certainty = 2.8 out of 5). The button press data analysis did not reveal any significant differences in the accuracy of the subject's responses between the pre- and post- exposure/sham rest period (p = 0.35, df = 1, 7 for sham; p = 0.15, df = 1,7 for real exposure).

The repeated measures ANOVA conducted on the extracted beta weight values from these ROI showed significant time by exposure interactions in these regions. In the left intraparietal sulcus, the interaction revealed a post-exposure deactivation that was stronger in the real exposure group as compared to the sham exposure group (F = 6.676, $p < 0.05$, df = 1,7, Figure 3). In Brodmann Area 19 a significant interaction showed that post-exposure activation was stronger in the sham exposure group as compared to the real exposure group (F= 7.426, $p < 0.05$, df = 1, 7).

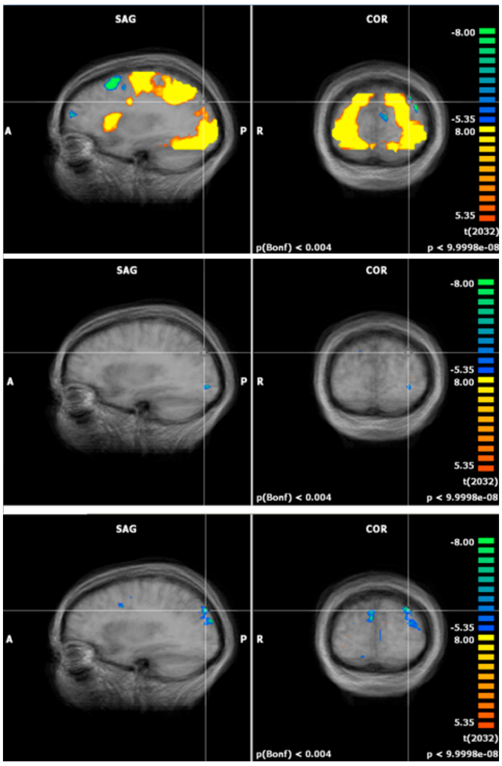

Figure 3. Activation in the left intraparietal sulcus during the mental rotation task. Top: Pre-exposure (n=9); Centre: Post-minus-pre-exposure in sham group (n=4); Bottom: Post-minus-pre- exposure in the real exposure group (n=5).

Summary

Brain regions associated with the mental rotation task in previous fMRI studies (Cohen et al., 1996) were activated in the pre-exposure results of the combined real and sham exposure groups. The Post- minus pre-exposure results demonstrated that the activation of specific brain regions associated with mental rotation task performance is altered after the real exposure. After the 60-minute 60 Hz, 3000 µT exposure, there was a significant decrease in activation in the intraparietal sulcus in the real exposure group and a stronger activation in the sham group in regions involved in visual processing. The main functions of the intraparietal sulcus are perceptual-motor coordination and visual attention, but this region may also play a role in visuospatial working memory (Todd & Marois, 2004), which are processes involved in the mental rotation task using the button press.

Exposure to an ELF MF did not have a significant effect on the speed or accuracy of the subjects' responses in the mental rotation task. Despite the differences in functional activation patterns following magnetic field exposure, blood flow changes were not associated with differences in the performance of the mental rotation task. This could be because functional imaging is a more sensitive technique for measuring the subtle effects of magnetic field exposure than behavioural performance, or possibly because the group differences seen reflect compensation for the effects of the field, to yield the same overall performance.

Although previous studies have not looked specifically at the effect of a magnetic field on the performance of the mental rotation task, a few have observed the effects of a magnetic field on speed and accuracy in other tasks, and have had varied results. Cook et al. (1992) observed a decrease in error in the reaction speed task after exposure to a 9 kV/m and 20 µT MF. However, Podd et al. (2002) did not find any effect on reaction time or accuracy in a visual discrimination task after exposure to a 50 Hz MF. Since the duration of exposure, the field strength and frequency and the task differ from study to study, this may cause the discrepancy in the reported results.

We can speculate on potential mechanisms, which may result in brain functional activation being modulated after MF exposure during a mental rotation task, without affecting the performance of the task. First, significantly decreased intraparietal sulcus functional activation could be a compensation mechanism from neuronal circuits in order to achieve the same outcome (i.e., task performance); second, changes in synaptic plasticity (efficiency of synapses in terms of evoking post-synaptic excitatory or inhibitory responses) could be induced by MF exposure. Small membrane depolarization induced by MF exposure could affect the timing of spikes, and thereby synaptic weights since synaptic plasticity is dependent on spike timing.

In summary, according to our results, one hour of exposure to an ELF MF at a frequency of 60 Hz and amplitude of 3000 μT modulates neuroprocessing during a mental rotation task, but does not affect speed or accuracy of the task. The ELF MF exposure had a selective effect on brain regions associated with visual attention and processing and the results of this study support the use of fMRI for observing the effect of ELF MF on the performance of cognitive tasks. Future work should observe the effect of different ELF MF field strengths and frequencies, different lengths of exposure to the ELF MF and the duration of the effect of ELF MF exposure after the field is turned off on performance of the mental rotation task.

Acknowledgments

The authors would like to acknowledge Dr. Jean Théberge for his help in programming the magnetic field in the MRI. This project was sponsored by Hydro-Québec (Canada), EDF-RTE (France), CIHR (Canada) and Lawson Health Research Institute.

References

Barnes, J., Howard, R.J., Senior, C., Brammer, M., Bullmore, E.T., Simmons, A., Woodruff, P., David, A.S. (2000). Cortical activity during rotational and linear transformations. *Neuropsychologia*, 38(8), 1148-56.

Carpenter, P.A., Just, M.A., Keller, T.A., Eddy, W., Thulborn, K. (1999). Graded functional activation in the visuospatial system with the amount of task demand. *Journal of Cognitive Neuroscience,* 11(1), 9-24.

Cohen, M.S., Kosslyn S.M., Breiter, H.C., DiGirolamo, G.J., Thompson, W.L., Anderson, A.K., et al., (1996). Changes in cortical activity during mental rotation: A mapping study using functional MRI. *Brain*, 119, 89-100.

Cook, C.M., Thomas, A.W., Prato, F.S., (2002). Human electrophysiological and cognitive effects of exposure to ELF magnetic and ELF modulated RF and microwave fields: a review of recent studies. *Bioelectromagnetics*. 23(2), 144-57.

Cook, M.R., Graham, C., Cohen, H.D., Gerkovich, M.M., (1992) A replication study of human exposure to 60-Hz fields: effects on neurobehavioral measures. *Bioelectromagnetics,* 13, 261-285.

Crasson, M., (2003) 50-60 Hz electric and magnetic field effects on cognitive function in humans: a review. *Radiation Protection Dosimetry,* 106, 333-340.

IEEE, P1555/D5 (2001). Standard for safety levels with respect to human exposure to electric and magnetic fields 0 to 3 kHz, IEEE: NY.

Johnson, A.M., (1990). Speed of mental rotation as a function of problem solving strategies. *Perceptual and Motor Skills*, 71, 803-806.

Jones, B., & Anuza, T., (1982). Effects of sex, handeness, stimulus and visual field on "mental rotation". *Cortex,* 18, 501-514.

Kurokawa, Y., Nitta, H., Imai, H., Kabuto, M., (2003) No influence of short-term exposure to 50-Hz magnetic fields on cognitive performance function in human. *International archives of occupational and environmental health,* 76, 437-442.

Oldfield, R.C., (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, 9(1),97-113.

Ogawa, S., Lee, T.M., Kay, A.R., Tank, D.W., (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings for the National Academy of Sciences* U S A. 87(24), 9868-72.

Podd, J., Abbott, J., Kazantzis, N., Rowland A., (2002) Brief exposure to a 50 Hz, 100 microT magnetic field: effects on reaction time, accuracy, and recognition memory. *Bioelectromagnetics,* 23, 189-195.

Preece, A.W., Wesnes, K.A., & Iwi, G.R., (1998) The effect of a 50 Hz magnetic field on cognitive function in humans. *International Journal of Radiation Biology,* 74,463-470.

Richter, W., Somorjai, R., Summers, R., Jarmasz, M., Menon, R.S., Gati, J.S., et al., (2000) Motor area activity during mental rotation studied by time-resolved single-trial fMRI. *Journal of Cognitive Neuroscience*, 12, 310-320.

Robertson, J.A., Theberge, J., Weller, J., Drost, D.J., Prato, F.S., Thomas, A.W., (2010) Low-frequency pulsed electromagnetic field exposure can alter neuroprocessing in humans. *Journal of the Royal Society*, Interface, 7, 467-473.

Shepard, R., & Metzler, J., (1971). Mental rotation of three dimensional objects. *Science,* 171(972), 701-3.

Tagaris, G.A., Kim, S.G., Strupp, J.P., Andersen, P., Uğurbil, K., Georgopoulos, A.P., (1996). Quantitative relations between parietal activation and performance in mental rotation. *Neuroreport*, 7(3), 773-6.

Todd, J.J., & Marois, R., (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature,* 428, 751-754

Vingerhoets, G., de Lange, F.P., Vandemaele, P., Deblaere, K., Achten, E., (2002) Motor imagery in mental rotation: an fMRI study. *Neuroimage,* 17, 1623-1633.

Wexler, M., Kosslyn, S.M., & Berthoz, A., (1998) Motor processes in mental rotation. *Cognition,* 68, 77-94.

Windischberger, C., Lamm, C., Bauer, H., Moser, E., (2003) Human motor cortex activity during mental rotation. *Neuroimage,* 20, 225-23.