**Bioelectromagnetics**

# Cognitive Function and Symptoms in Adults and Adolescents in Relation to RF Radiation From UMTS Base Stations

**Ingunn S. Riddervold,[1] Gert F. Pedersen,[2] Niels T. Andersen,[3] Anders D. Pedersen,[4] Jørgen B. Andersen,[2] Robert Zachariae,[5] Lars Mølhave,[1] Torben Sigsgaard,[1] and Søren K. Kjærgaard[1]***

[1]*Department of Environmental and Occupational Medicine, Institute of Public Health, University of Aarhus, Aarhus, Denmark*
[2]*Department of Electronic Systems, University of Aalborg, Aalborg, Denmark*
[3]*Department of Biostatistics, Institute of Public Health, University of Aarhus, Aarhus, Denmark*
[4]*Hammel Neurorehabilitation and Research Center, Hammel, Denmark*
[5]*Psychooncology Research Unit, Aarhus University Hospital, Aarhus, Denmark*

There is widespread public concern about the potential adverse health effects of mobile phones in general and their associated base stations in particular. This study was designed to investigate the acute effects of radio frequency (RF) electromagnetic fields (EMF) emitted by the Universal Mobile Telecommunication System (UMTS) mobile phone base stations on human cognitive function and symptoms. Forty adolescents (15–16 years) and 40 adults (25–40 years) were exposed to four conditions: (1) sham, (2) a Continuous Wave (CW) at 2140 MHz, (3) a signal at 2140 MHz modulated as UMTS and (4) UMTS at 2140 MHz including all control features in a randomized, double blinded cross-over design. Each exposure lasted 45 min. During exposure the participants performed different cognitive tasks with the Trail Making B (TMB) test as the main outcome and completed a questionnaire measuring self reported subjective symptoms. No statistically significant differences between the UMTS and sham conditions were found for performance on TMB. For the adults, the estimated difference between UMTS and sham was −3.2% (−9.2%; 2.9%) and for the adolescents 5.5% (−1.1%; 12.2%). No significant changes were found in any of the cognitive tasks. An increase in 'headache rating' was observed when data from the adolescents and adults were combined ($P = 0.027$), an effect that may be due to differences at baseline. In conclusion, the primary hypothesis that UMTS radiation reduces general performance in the TMB test was not confirmed. However, we suggest that the hypothesis of subjective symptoms and EMF exposure needs further research. Bioelectromagnetics. © 2007 Wiley-Liss, Inc.

**Key words: exposure study; humans; tests; trail making; subjective symptoms**

## INTRODUCTION

The global increase in the use of mobile phones and the number of mobile phone base stations is accompanied by increased concerns about possible health risks due to their emitted radio frequency (RF) electromagnetic field (EMF), especially with respect to mobile phone base stations.

The relation between human health and EMF has been reviewed recently [Roosli et al., 2003; Feychting et al., 2005]. In an observational study mobile phone EMF exposure has been related to symptoms of sleep-disorders, headaches, nervousness, fatigue, and concentration difficulties [Al-Khlaiwi and Meo, 2004]. Other observational studies have confirmed the association between mobile phone-related EMF and headache [Chia et al., 2000; Sandström et al., 2001]. It has been suggested that EMF from mobile phones may influence cognitive function in humans through either thermal or non-thermal effects on protein

---

Grant sponsor: Danish Strategic Research Council "Programme Commission on Non-ionizing Radiation"; Grant number: 2064-04-0009.

*Correspondence to: Søren K. Kjærgaard, Institute of Public Health, University of Aarhus, Vennelyst Boulevard 6, Building 1260, DK-8000 Aarhus C, Denmark. E-mail: skk@mil.au.dk

Received for review 21 January 2007; Final revision received 12 October 2007

DOI 10.1002/bem.20388

production [Preece et al., 1999]. In experiments exploring the effects of EMF on cognitive or sensory processing in humans, the tasks have typically involved reaction time (RTI), sensory discrimination, and working memory. In an experimental study investigating the effect of ELF magnetic field on human RTI no significant effects on performance after exposure were found [Podd et al., 1995] whereas Koivisto and colleagues showed that RTI was speeded up when investigating the effects of 902 MHz EMF emitted by mobile phones [Koivisto et al., 2000]. Lass et al. [2002] showed that acute 7 Hz-modulated 450 MHz electromagnetic radiation may affect processes such as attention and short term memory resulting in a decreased number of errors for less complicated neuropsychological tasks and increased number of errors for more complicated ones. Facilitated performance under exposure to 900 MHz mobile phone EMF was established in a study by Edelstyn and Oldershaw [2002], while Haarala et al. [2004] found no such effect. Maier et al. [2004] showed that participants' cognitive performance was impaired after exposure to pulsed EMF.

The majority of research has focused on exposure from the phone itself while the effects from base stations have received less attention probably due to the low exposure level they induce. However, symptoms of discomfort have also been related to mobile phone base stations [Hutter et al., 2006]. One of the first controlled studies of mobile phone base stations (often referred to as the TNO-study) investigated the effects of the EMF emitted by GSM and UMTS base-stations [Zwamborn et al., 2003], and found statistically significant relations between UMTS-like fields with a field strength of 1 V/m and reported symptoms. The TNO-study was an exploratory study in this area, and it was a natural consequence that the validity of the results should be clarified by replication studies. Such a replication study was recently published. In this study neither well-being nor cognitive performance was found to be affected by UMTS-like fields [Regel et al., 2006]. Another study with comparable exposure has reported more symptoms among sensitive individuals [Eltiti et al., 2007]. However, further analysis revealed that this finding was probably due to the effect of exposure order rather than the exposure itself.

The objective of the present study was not to replicate the TNO-study, but to assess the effect of EMF on symptoms and cognitive function in adults and adolescents and focus on UMTS-related exposure conditions. Our aim was to assess the effects of low intensity electromagnetic radiation, related to modern antenna masts supporting mobile communications. The primary hypothesis was that UMTS radiation reduces the speed of the Trail Making B (TMB), a test which is sensitive to impairment in multiple cognitive domains. If the hypothesis was confirmed, it would then be relevant to evaluate the characteristics of the radiation that are responsible for the reaction. Therefore, two exposures of relevance with some of the basic components of the UMTS signal were added. The secondary hypothesis was that exposure to UMTS-like radiation reduces cognitive performance and increases symptoms of the participants, and that adolescents may be more sensitive to this type of EMF than adults [Kheifets et al., 2005].

## MATERIALS AND METHODS

### Design

A randomized double blind, cross-over design using the six different 4 × 4 Latin squares was applied to ensure that all possible exposure orders were represented equally. The order of the different Latin squares and the order of the four participants within each of the six Latin squares were chosen randomly. The randomization across the exposure condition was carried out by an external consultant using a computer to ensure blinding, achieve complete randomization, and obtain a fully balanced study. During the sessions, neither the participants nor the investigators were aware of exposures. Double blinding was further ensured by having the same noise level (acoustic and electric) related to the exposure. The investigator monitoring the exposure had no contact with the participants or clinical staff during measurement, but controlled the sessions entirely over the internet. The blinding was continued until the basic statistical analyses had been conducted.

All participants attended four exposure sessions: three exposure types and a sham exposure pursuant to the Latin square effect with at least 24 h between each session. Exposure sessions were performed on separate days at the same time of day. Each session included completion of a computer-based questionnaire at baseline followed by a 45 min. exposure. During exposure, participants completed one paper-and-pencil test, were exposed to three cognitive tasks on the computer, and finally completed the questionnaire a second time.

### Participants

The national Civil Person Registration (CPR) was used to identify 15- to 16-year-old adolescents and adults aged 25–40 years living in Aarhus County, Denmark. The participants were recruited by a mail-out invitation. Seven hundred fifty participants in each group were selected at random from the registry. Participants were enrolled on 'first-come, first-served' basis. Eighty-nine adolescents and 84 adults participated in the pre-investigation. All volunteers completed a health questionnaire and went through a medical examination. Exclusion criteria were pregnancy, a medical history of head injuries and/or neurological/psychiatric diseases. Further exclusion criteria were based on the result of three tasks performed after the medical examination; the Danish Adult Reading Test (DART), Raven Advanced Progressive Matrices (RPM) and TMB. The exclusion criteria were test results outside the range of the normative mean ± 2 SD [Gade and Mortensen, 1984; Warrington, 1984]. Informed written consent was required from all participants. For the adolescents the informed consent had to be signed by themselves and at least one lawful guardian. After the pre-investigation, 23 adolescents and 13 adults were excluded from the study. A group of 40 adolescents (17 males, 23 females, mean age 15.7; SD 0.48) and 40 adults (24 males, 16 females, mean age 31.3; SD 4.5) participated in the study. The rest of the group was held on stand-by in case of sickness or withdrawals. The study was approved by The Aarhus County Human Study Review Board in accordance with the regulations for the protection of the participants (Ref. no. 20050032).

### Exposure Facilities

The study was performed at the Department of Environmental and Occupational Medicine, University of Aarhus. Sessions took place under controlled conditions in a 33.4 $m^3$ climate chamber made of aluminium. To improve shielding in the chamber from EMF outside the chamber, all metal joints were covered with aluminium tape and metal spring-fingers were mounted at the door. The shielding was improved by minimum 25 dB over the frequency range from 20 MHz to 6 GHz, and no mobile phones were allowed on the floor where the chamber was located. Inside the chamber walls, the floor and ceiling were partly covered with RF absorbers to prevent reflections, etc. Furthermore, all cable connections to and from the chamber were filtered at the entrance and ferrite beads were mounted on the cables to suppress all common mode signals. To minimize extremely low frequency (ELF) fields stemming from the main power supply (50 Hz), all lighting in the room close to the participant (less than 1 m) was from light-fibers, whereas light more than 2.5 m from the participant originated from a 12 V DC source. All other electronic devices like the computer screen and camera were supplied by 12 V DC. Except for cables to the press pad and screen, there were no other non-intended electromagnetic radiators in the chamber. Inside the chamber, participants were exposed to the different exposure types to record their acute subjective responses to the exposure. Participants sat at a desk within the chamber. Throughout each session, the participant was asked to maintain a sitting posture on the chair next to the table (see Fig. 1 for an overview of the setup).

The test administrator operated the task session using a connected computer positioned in a control room adjacent to the climate chamber. A two-way audio communication system was used to communicate with the participant, and a video-surveillance camera was used to observe the participant during the entire session. This setup prevented disturbance by other persons in the chamber and the movements of the participant were minimized, ensuring similar exposures.

An effort was made to minimize other exposures that could influence the results. This was ensured by an air-conditioning system controlling air-flow and temperature. The temperature, humidity and air-flow were monitored during exposure. The air was analyzed for volatile organic compounds and particulates before and after the study, as were parameters including light intensity and noise level. No significant exposure levels were observed.

### RF Exposure Generation

In this study a signal level of 1 V/m (2.6 mW/$m^2$) was targeted. This level corresponds to the level experienced by the general public living close to a base station antenna, typically between 20 and 100 m; the lowest level being inside a building [Andersen and Pedersen, 2004]. The exposure set-up was designed to obtain an exposure similar to the exposure from a base station at a distance of some 20 m or more and therefore be a plane wave with linear polarization. Each participant was exposed to a combination of four possible exposure types; sham, CW at 2140 MHz, a signal at 2140 MHz

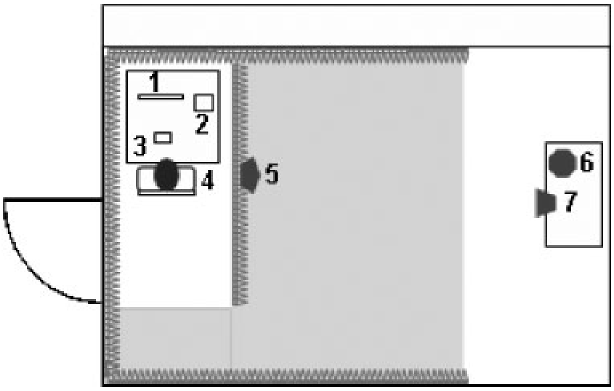

Fig. 1. Sketch of the exposure chamber. Walls, floor and the ceiling are partly covered by pyramidal RF absorbers. (1) Touch computer screen. (2) Two-way audio communication system. (3) CANTAB press-pad. (4) Participant. (5) Wideband probe antenna. (6) Video-surveillance camera. (7) Radiating antenna.

modulated as UMTS and UMTS at 2140 MHz including all control features. The peak background ELF magnetic field was measured to 70 nT and observed at 50 Hz. The background RF-field was measured from 10 MHz to 6 GHz to be less than 0.001 V/m which was 100 times less than the value outside the room at the worst frequency which was approximately 330 MHz.

To ensure a plane wave, the chamber was modified by clean room RF-absorbers (type: EHP-5PCL and FL-2250CL from ETS, Texas) on all four walls and a medium gain antenna (8dBi, from Huber & Suhner Pfäffikon, Switzerland model SPA 2100/80/8) was used as a compromise between needed absorbers and size of the volume with plane wave condition. The antenna was mounted to radiate vertical polarization. The participants were located 2.8 m from the radiating antenna and seated on a chair at a wooden table next to the computer and keyboard. The field strength measured (by a Chauvin Arnoux Paris, France CA-43 device) in a $0.5 \times 0.7$ m area of a 0.1 by 0.1 m grid area were between 0.9 and 2.2 V/m (excluding the outer 0.1 m resulted in 1.5–2.2 V/m). No participants moved outside this area while exposed.

To control the intended exposure and possible changing external exposure, a wideband probe antenna (Huber & Shunner SWA 0869/360/4/10/V) was mounted close to the participants (0.1 m above the absorber at the floor) between the radiating antenna and the participants. The probe was connected to a spectrum analyzer (Agilent E4440A), which monitored the frequency spectrum from 20 to 6 GHz with a sweep each second averaged for 45 s. and transferred each minute.

All exposure signals were generated by a Rohde & Schwarz CMU200 with the wide band UMTS module. The CW modulated as UMTS was generated by setting the control channels to the lowest level (P-SCH, S-SCH, P-CCPCH, and the PICH channel). The UMTS signal was generated by initiating a live connection to a mobile phone (Sony Ericsson Z800i) through a 10 dB coupler and then filtering only the base station signal (the downlink frequency of 2140 MHz, using a K&L Microwave B24 downlink filter) to the exposure antenna. Settings on the CMU for the UMTS exposure were; UE max power 33 dBm, UE target power −40 dBm. To ensure blinding, voice recognition by the phone was arranged. The computer controlling the exposure set up controlled a generator connected to the microphone input of the phone to answer the call without involving any lab personnel.

## Cognitive Tests

The computer-administered Cambridge Neuropsychological Test Automated Battery (CANTAB *eclipse*$^{\text{TM}}$) was used to examine specific components of cognition. The participants were instructed to respond to stimuli presented on a computer screen by pressing a specific button on a press-pad or touch screen as accurately as possible. Three tests were chosen to evaluate simple and complex RTI, vigilance, attention and memory; RTI, Rapid Visual Information Processing (RVP) and Paired Associated Learning (PAL). Each session started with 5 min exposure before the testing was initiated due to the findings of Oftedal et al. [2000], which suggested that exposure must last at least 5 min before symptoms occur. After completing the first test, the participant was automatically given the next, thereby completing the three tasks in 10–20 min.

RTI measures the participant's speed of response to a visual target (reaction and movement time). In the simple RTI task, the participant had to hold the pressure pad down, then release it and touch the screen as quickly as possible when a yellow dot appeared in the center. In the complex (5-choice) reaction task, the yellow dot appeared in any one of five locations. A parallel test mode was used.

Clinical Mode of RVP was used to measure general performance of vigilance and attention. In the RVP a white box appeared in the center of the computer screen with digits from 2 to 9 appearing inside, in a pseudo-random order at the rate of 100 digits per minute. Participants were requested to detect target sequence of digits (2–4–6, 3–5–7 and 4–6–8) and to register their responses using the press pad. Target sequences occurred at the rate of 16 every 2 min. For RVP only the outcome 'RVP A' was used. 'RVP A' is the signal detection measure of sensitivity to the target, regardless of response tendency (range 0.00–1.00; bad to good).

Parallel Modes of PAL is a delayed response procedure assessing visual memory and new learning. The test has different stages which had to be completed in sequence. For each stage, boxes were displayed on the screen and opened in a randomized order. One or more of them contained a pattern. The patterns shown in the boxes were then displayed in the middle of the screen one at a time, and then the participant had to touch the box where the pattern was originally displayed. When the participant had all the locations correct, they proceeded to the next stage. If the participant could not complete a stage correctly, the test terminated. Clinical mode is typically used when running only once whereas parallel mode (if available) is used for repeated testing to ensure that the order and patterns are displayed differently at each test section to minimize learning effect.

The TMB was chosen as the primary outcome, as it is a well-established test found to be sensitive to impairment in multiple cognitive domains (psychomotor speed, attention, and executive function) [Lezak et al., 2004; Tombaugh, 2004]. This paper-and-pencil test was initiated after 35 min of exposure. In TMB, which was used in this experiment, the participant had to draw lines alternating between numbers and letters in consecutive order. The exact same test was used in each session and performance was assessed by the time taken to complete the trial correctly. Normally errors during task completion require immediate correction and the performance is measured as the speed at which the task is correctly completed [Keetley et al., 2001]. However, the video camera did not produce a sufficiently detailed picture of the participant completing the tests to detect these errors. Therefore, the test procedure was altered. After completing the test, participants were asked to repeat the order of the connected numbers and letters. If an error was detected, the participant had to repeat the test. Only the time for the new completed test was used. Staff members administering the tests were trained and approved by the clinical neuropsychologist in the project group.

### Subjective Symptoms

During each session a questionnaire assessing self reported subjective symptoms or perception was completed prior to (baseline) and at the end of the exposure session. The participants were asked to rate the strength of the symptom and perception on a Visual Analogue Scale (VAS) ranging from ‘‘not at all’’ (0) to ‘‘very much’’ (202 mm) on a computer touch screen. The questionnaire included four control items concerning the exposure, air quality, humidity and temperature and 11 items concerned with symptoms or perceptions, for example, concentration difficulties, tingling or pain, headache, nausea, dizziness, and claustrophobia. This study focused a priori on ‘headache’ and ‘concentration difficulties’ as secondary hypotheses as these symptoms could trigger the remaining symptoms. All the tests as well as the computer-based questionnaire were presented along with the instructions in one practice session before actual testing. Each outcome was measured as an absolute change from baseline to end of the session (in mm) on the VAS.

### Analysis

Data collection and documentation was achieved according to good clinical practice [European Medicine Agency, 2002]. All data were sampled by or stored on a laptop computer. Data entry was performed in duplicate independently by two persons. A statistical analysis plan was developed and sent to The Danish Council for Strategic Research, Programme Commission on Non-ionizing Radiation before the initiation of the investigation. After all the exposure sessions and before any information about the exposures was unblinded, the collected data were analyzed to decide the final analysis strategy. This strategy was described in an addendum to the analysis plan, which was likewise sent to the same authority before interruption of the blinding. The outline of the addendum is listed below.

In the three variables TMB (Primary outcome), RTI (complex RTI) and RTI (complex movement time) all times were measured. It was appropriate to analyze the data log-transformed by an ANOVA model including study day, exposure, group (adult/adolescent) as fixed effects and participants (persons) as a random factor. All four exposures were included in the analysis, but only the difference between the sham exposure and the UMTS base station signal exposure (typical base station signal, 2140 MHz, modulated with control signals) were of interest. The differences were estimated for adults and adolescents independently and compared. If no significant difference between adults and adolescents was found, the common difference was estimated. These variables are described by the geometric mean, coefficient of variance (CV), relative difference between exposures including 95% confidence interval (CI) and $P$-value.

It was not appropriate to analyze the data of the other secondary outcomes ‘RVP A,’ ‘PAL,’ ‘Headache’ (change from baseline) and ‘Concentration difficulties’ (change from baseline) and measurements on scales by an ANOVA model due to ceiling and flooring problems, heterogeneity in the (within participant) variation or assumption on normal distributed data. Subjective symptoms at baseline are described by median and the inter quartile range. The data from RVP A, ‘change in headache’ and ‘change in concentration’ for both exposures and the difference between the two exposures are described by box-plots. The upper adjacent value in the plot is the largest data-point smaller than the 75th percentile plus 3/2 times the inter quartile range. The lower adjacent value is defined in a similar way.

To compare sham exposure and UMTS base station signal exposure and taking into account a possible ‘learning effect’ we analyzed the data by a standard technique from cross-over trials: We divided the participants into two groups; Group S: participants with the sham exposure before the UMTS base station signal exposure; Group E: participants with the UMTS base station signal exposure before the sham exposure. The hypothesis of no difference between sham exposure and UMTS base station signal exposure was then tested by comparing the two groups (S and E) with respect to the differences between the first and the second measurement, for example, for participants in group S: (sham−UMTS) and participants in group E:

(UMTS−sham). We used a Wilcoxon Rank sum test to compare groups S and E and a stratified (stratification on group S and group E) Wilcoxon Rank sum test to compare adults and adolescents.

After eliminating blinding and analyzing 'Headache' (change from baseline) and 'Concentration difficulties' (change from baseline) it was decided to describe the measurements at baseline, at the end of the exposure and the changes by calculating; (1) The number of participants where the measurements from the two exposures are equal, (2) the number of participants where the measurement from the UMTS base station signal exposure is largest and (3) the number of participants were the measurement from the sham exposure is largest.

Further, it was decided after eliminating blinding that additional analyses should be made to elucidate the possible effects of the altered TMB test procedure on learning and the results of the primary outcome. Based on a within-participant coefficient of variation of 10% in the TMB [Tombaugh, 2004] and an expected 5% observed change in the mean, it was calculated that the suggested group size of 40 would yield a statistical power of 87%. This was considered sufficient.

## RESULTS

Baseline symptoms and perception status for adolescents and adults are listed in Table 1. Only minor differences between the two exposures were observed.

### Primary Outcome

The results of the TMB test are shown in Table 2. In general the adults were 16.4% (95%CI: 3.2%; 29.6%) faster than the adolescents ($P = 0.015$). The standard deviation of the relative difference between the UMTS and the sham within a person was estimated to be 19% for adults and 21% for adolescents.

There were no significant differences between UMTS and sham exposure for the adults and adolescents when analyzed separately. The primary analysis showed a significant ($P < 0.001$) effect of learning throughout the study with a reduction in time used of 7−10% from day to day with no significant difference between adults and adolescents ($P = 0.42$). The estimated overall improvement from days 1 to 4 was 29% (25%; 34%). Comparison of adults and adolescents with respect to the difference between UMTS and sham exposure approached statistical significance ($P = 0.056$) and the overall difference for the two groups was estimated to be 1.2% (−3.2%; 5.7%), which did not reach significance ($P = 0.60$).

In 42 of the 320 TMB tests, the participants made errors and the test was repeated. The adults accounted for 22 errors (8 UMTS, 6 Sham) and the adolescents for 20 errors (5 UMTS, 6 Sham). The data were therefore analyzed including information on whether the TMB test was repeated or not to adjust for its overall effect. For the adults, the estimated difference between the UMTS and sham condition was −3.9% (−9.6%; 1.9%) and for the adolescents 5.5% (−1.2%; 12.0). Comparison of adults and adolescents with respect to the difference between UMTS and sham exposure now reached statistical

**TABLE 1. Symptoms and Perception at Baseline Assessed by the Computerized Visual Analogue Scale Under Exposure to Sham are Illustrated by Age Groups (40 Adults, 40 Adolescents)**

| | Adolescents (15–16 years) | | | | Adults (25–40 years) | | | |
|---|---|---|---|---|---|---|---|---|
| | UMTS | | Sham | | UMTS | | Sham | |
| Variable | Median | IqR | Median | IqR | Median | IqR | Median | IqR |
| Sense of air temperature | 0.53 | (0.50;0.60) | 0.51 | (0.48;0.57) | 0.51 | (0.49;0.56) | 0.50 | (0.50;0.55) |
| Sense of air humidity | 0.49 | (0.40;0.51) | 0.48 | (0.39;0.50) | 0.48 | (0.32;0.51) | 0.49 | (0.40;0.51) |
| Sense of air quality | 0.09 | (0.01;0.27) | 0.11 | (0.00;0.26) | 0.04 | (0.00;0.20) | 0.06 | (0.01;0.16) |
| Sense of sweat | 0.01 | (0.00;0.10) | 0.02 | (0.00;0.15) | 0.06 | (0.01;0.14) | 0.06 | (0.01;0.21) |
| Sense of chilling | 0.02 | (0.00;0.12) | 0.04 | (0.00;0.12) | 0.04 | (0.01;0.12) | 0.02 | (0.00;0.08) |
| Sense of breathlessness | 0.01 | (0.00;0.06) | 0.01 | (0.00;0.07) | 0.02 | (0.00;0.05) | 0.02 | (0.00;0.06) |
| Sense of tingling | 0.01 | (0.00;0.09) | 0.02 | (0.00;0.07) | 0.02 | (0.00;0.05) | 0.01 | (0.00;0.04) |
| Sense of pain | 0.00 | (0.00;0.01) | 0.01 | (0.00;0.05) | 0.01 | (0.00;0.05) | 0.02 | (0.00;0.04) |
| Sense of sleepiness | 0.15 | (0.00;0.22) | 0.16 | (0.00;0.34) | 0.04 | (0.00;0.16) | 0.03 | (0.00;0.09) |
| Sense of nausea | 0.00 | (0.00;0.02) | 0.00 | (0.00;0.03) | 0.00 | (0.00;0.05) | 0.01 | (0.00;0.03) |
| Sense of dizziness | 0.01 | (0.00;0.06) | 0.00 | (0.00;0.04) | 0.02 | (0.00;0.06) | 0.01 | (0.00;0.03) |
| Sense of headache | 0.00 | (0.00;0.04) | 0.01 | (0.00;0.08) | 0.10 | (0.00;0.05) | 0.02 | (.000;0.06) |
| Sense of concentration difficulties | 0.03 | (0.00;0.09) | 0.02 | (0.00;0.08) | 0.01 | (0.00;0.07) | 0.02 | (0.00;0.08) |

Symptoms and perceptions at baseline are described by median and the inter quartile range (IqR).

TABLE 2. Cognitive Performance Measured by Trail Making B, Reaction and Movement Time in the RTI-Test* in 40 Adults and 40 Adolescents Exposed to UMTS and Sham

| | | UMTS | | Sham | | UMTS–Sham | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Geometric | | Geometric | | | | | |
| Outcome | Group | Mean | cv | Mean | cv | Difference | 95% CI | | *P*-Value |
| Trail making B (s) | | | | | | | | | |
| | Adolescents (15–16 years) | 56.6 | 33% | 53.6 | 36% | 5.5% | −1.1% | 12.2% | 0.10 |
| | Adults (25–40 years) | 47.9 | 28% | 49.6 | 31% | −3.2% | −9.2% | 2.9% | 0.30 |
| Reaction time in RTI-test (ms) | | | | | | | | | |
| | Adolescents (15–16 years) | 310.5 | 11% | 307.3 | 10% | 1.0% | −1.5% | 3.6% | 0.42 |
| | Adults (25–40 years) | 317.3 | 12% | 311.9 | 12% | 1.7% | −0.8% | 4.2% | 0.18 |
| Movement time in RTI-test (ms) | | | | | | | | | |
| | Adolescents (15–16 years) | 310.8 | 20% | 317.3 | 16% | −2.1% | −7.5% | 3.3% | 0.45 |
| | Adults (25–40 years) | 302.4 | 22% | 302.9 | 20% | −0.1% | −4.0% | 3.8% | 0.95 |

*RTI-test is a part of the CANTAB Eclipse test battery measured in milliseconds. Outcomes are described by the geometric mean, confidence variance (CV), relative difference between exposures including 95% confidence interval (CI) and *P*-value.

significance ($P = 0.038$). For the adults, the response to the TMB tests with errors were 13.2% (6.1%; 20.2%) slower compared to the response to tests without errors. For the adolescents, tests with errors were completed 2.0% (−6.6%; 10.7%) faster compared to the tests without errors. This difference between the adults and the adolescents was significant ($P = 0.007$). The analysis taking into account that some of the participants had more than four repetitions (up to 9) of the TMB test yielded comparable results.

## Secondary Outcome

The results of the RTI Five Choice tests (reaction and movement time) for both adults and adolescents can be seen in Table 2. The analysis showed no significant effects of learning for RTI for adults ($P = 0.57$), adolescents ($P = 0.28$) or the combined group ($P = 0.22$). Comparison of the UMTS signal and the sham exposure for adults and adolescents was not significant ($P = 0.71$) and the overall difference is estimated to be 1.3% (−0.4%; 3.1%) which was not significant ($P = 0.12$). The RTI was 1.7% (−3.1%; 6.6%) slower for the adults compared to the adolescents ($P = 0.48$). The primary analysis showed a significant ($P < 0.001$) effect of learning for movement time with no significant difference between adults and adolescents ($P = 0.27$). The overall estimated improvement from days 1 to 4 was 7.5% (95%CI: 4.2%; 10.9%). The difference between the UMTS signal compared to the sham exposure for adults and adolescents was not significant ($P = 0.56$) and the common difference is estimated to be −1.1% (−4.4%; 2.2%), which was not significant ($P = 0.52$). In general the adults were 4.0% (−3.3%; 11.4%) faster than the adolescents ($P = 0.28$).

The results of the other secondary outcomes are presented in Table 3, Figures 2 and 3. The difference between the UMTS signal compared to the sham exposure for adults and adolescents was not significant in any of the outcomes including RVP A ($P = 0.50$), PAL ($P = 0.31$), change from pre- to post-exposure of 'headache' symptoms ($P = 0.31$) or change in 'concentration difficulties' ($P = 0.58$). Combining adults and adolescents in a stratified analyses showed no significant difference between the UMTS signal compared to the sham exposure for RVP A ($P = 0.96$), PAL ($P = 0.51$) and change in 'concentration difficulties' ($P = 0.13$), but a significant difference in change in 'headache' ($P = 0.027$). In Table 4 'concentration difficulties' and 'headache' is presented as direction of difference between the two exposures. At the 'end' the perception of 'Concentration difficulties' and 'Headache' are almost equal between exposures, whereas both perceptions are noticeably higher at baseline for sham.

## DISCUSSION

No significant differences between UMTS and sham sessions were found; either for adults or for adolescents. One explanation could be too little power to detect the effect. The study was designed to detect a 5% change in TMB. The observed difference was 5.5% in adolescents which then should have had a high chance of being significant. The failure to detect a difference may be explained by the variation being twice as high as expected in the power analysis. The only way to resolve this is to repeat the study with a larger number of participants.

In addition, we observed a consistently high degree of learning in the TMB test during all four exposure sessions, which may complicate the interpretation of data. Although the learning effect was

**TABLE 3. Cognitive Performance Measured by Paired Associated Learning Test[†] in 40 Adults and 40 Adolescents Exposed to Sham and UMTS Radiation at 2140 MHz**

| | | Adolescents (15–16 years)* | | Adults (25–40 years)** | |
|---|---|---|---|---|---|
| | | UMTS | Sham | UMTS | Sham |
| Outcome | Number of patterns | No. of participants | No. of participants | No. of participants | No. of participants |
| PAL | | | | | |
| | 2 | 0 | 1 | 2 | 1 |
| | 3 | 13 | 13 | 14 | 14 |
| | 6 | 20 | 19 | 21 | 18 |
| | 8 | 7 | 7 | 3 | 7 |

[†] Paired Associated Learning reported as the 'Stage Completed on first trail' defined as the number of problems that the participant managed to complete on the first attempt. The test is a part of the CANTAB Eclipse test battery.

*$P$-value for the comparison of UMTS and sham ($P = 0.87$).

**$P$-value for the comparison of UMTS and sham ($P = 0.28$).

consistent over time and within the groups, and the analyses including this parameter did not account for the difference, they actually explained some of the variation observed. The comparison between adolescents and adults was almost significant ($P = 0.056$). Analysis adjusting for learning effect showed that this was not the case; actually it lowered the $P$-value further.

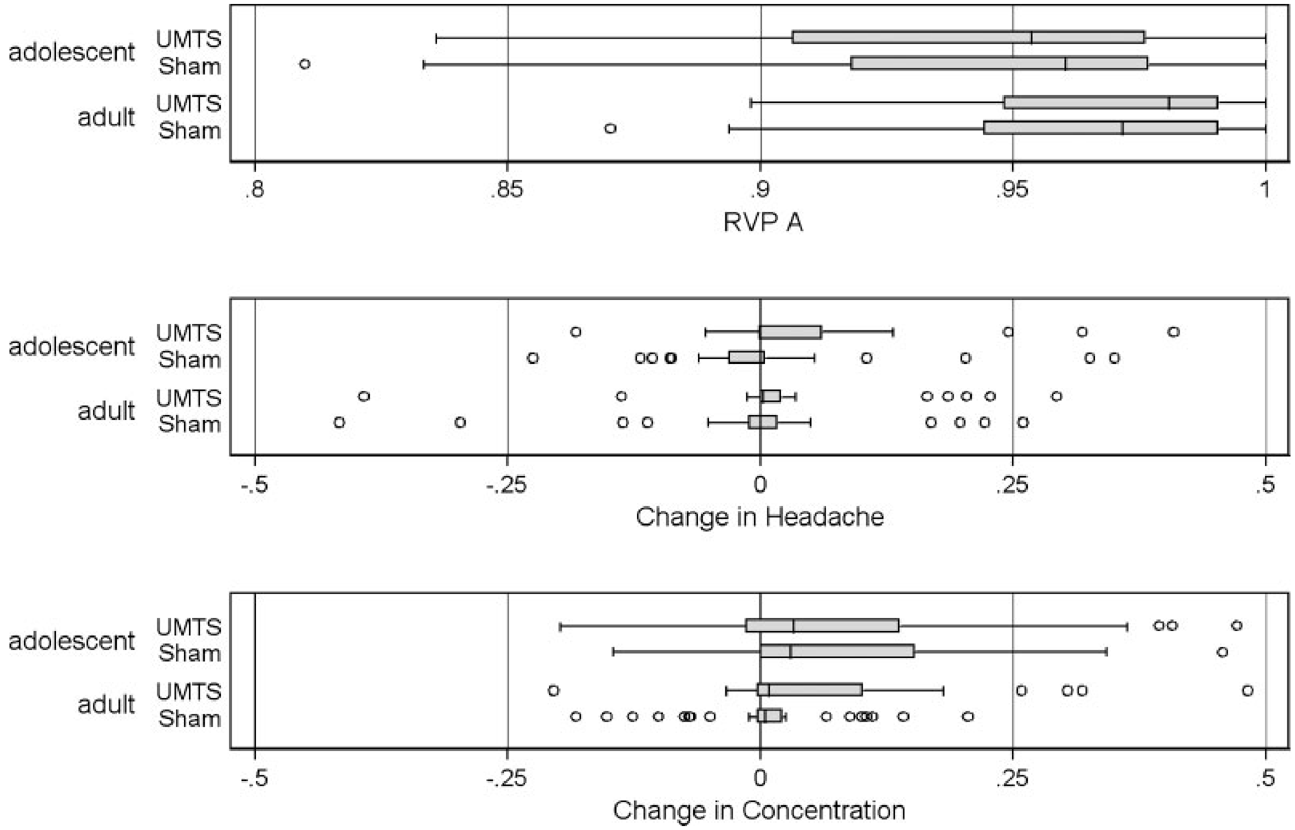

Fig. 2. Box plots for Rapid Visual Information Processing (RVP), 'change in headache' and 'change in concentration' after exposure to sham and UMTS radiation at 2140 MHz divided on age groups. *Note*: Upper adjacent value is the largest data-point smaller than the 75th percentile plus 3/2 times the inter quartile range. The lower adjacent value is defined in a similar way. The dots refer to single values outside the 75th percentile.

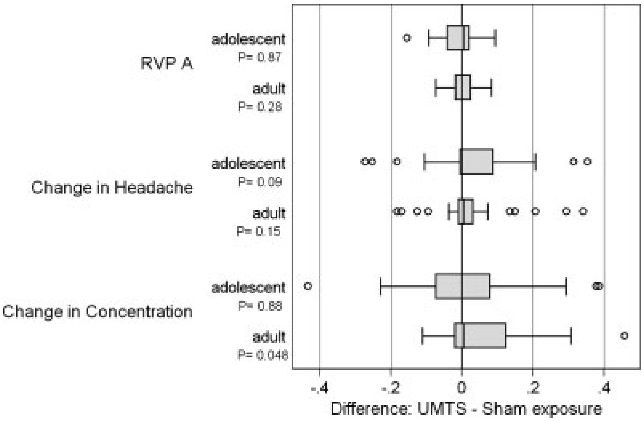

Fig. 3. Box plots illustrating the difference between sham and UMTS exposure for RVPA, 'change in headache' and 'change in concentration'. *Note*: Upper adjacent value is the largest data-point smaller than the 75th percentile plus 3/2 times the inter quartile range. The lower adjacent value is defined in a similar way. The dots refer to single values outside the 75th percentile.

Due to our secondary hypotheses, it was also assessed whether exposure to UMTS base station radiation would impair different aspects of human cognitive performance or produce subjective symptoms. RTI, PAL and RVP were the tasks chosen to measure impacts on different aspects of cognitive function. No effect was observed in any of the three tasks. This could of course be due to lack of effect on these functions. However, there are problems with respect to the sensitivity of these tests, due to the observed 'ceiling effect' in PAL and RVP, where several participants reached the maximum possible score of 1. It should therefore be reassessed whether these two cognitive tasks are sensitive enough to reliably measure minor potential EMF effects on healthy participants. An overall effect (adults and adolescents combined) for the self reported 'headache' ($P = 0.027$) was observed. In addition an effect on self reported 'concentration difficulties' in adults was observed ($P = 0.048$). However, the interpretation of the VAS data is complicated due to the fact that the perception changes from baseline can be unchanged, improved and worsened. Further, the majority of the participants perception is zero or in the proximity of zero. Our data indicated that baseline score for sham was higher than for UMTS (see Table 4). The observed effect may therefore be due to these differences at baseline.

The double blinded, randomized and outbalanced design is a powerful method to reduce the possibility that other factors confound the results. The randomization and blinding worked as intended. After exposure to UMTS 35 out of 80 participants answered 'yes' to the question; "*do you think you have been exposed to electromagnetic radiation*"? After sham exposure 31 out of 80 participants answered 'yes' to the same question. Therefore during the sessions, neither the participants nor the investigators were aware whether the participants were exposed or not, and accordingly they did not know which field-type was applied. Temperatures and humidity were monitored during the exposures as they are both important factors for cognitive performance and in particular for

**TABLE 4. Number of Participants with Symptoms of 'Concentration Difficulties' and 'Headache' Rated at Baseline and at the End of Exposure During Sham and UMTS Exposure (40 Adults, 40 Adolescents)**

| | | | No. of participants | | |
|---|---|---|---|---|---|
| Outcome | Group | Direction of difference[a] | Baseline | End | Change[b] |
| 'Concentration' | Adolescents (15–16 years) | UMTS equal to Sham | 10 | 4 | 4 |
| | | UMTS worse than Sham | 12 | 17 | 18 |
| | | Sham worse than UMTS | 18 | 19 | 18 |
| | Adults (25–40 years) | UMTS equal to Sham | 8 | 6 | 3 |
| | | UMTS worse than Sham | 12 | 17 | 22 |
| | | Sham worse than UMTS | 20 | 17 | 15 |
| 'Headache' | Adolescents (15–16 years) | UMTS equal to Sham | 15 | 13 | 10 |
| | | UMTS worse than Sham | 8 | 14 | 19 |
| | | Sham worse than UMTS | 17 | 13 | 11 |
| | Adults (25–40 years) | UMTS equal to Sham | 7 | 7 | 5 |
| | | UMTS worse than Sham | 11 | 19 | 22 |
| | | Sham worse than UMTS | 22 | 14 | 13 |

[a] Direction of differences is divided into the number of participants' who experienced 'Concentration difficulties' or 'Headache'; equally during UMTS and sham; worse during UMTS than sham; or worse during sham than UMTS exposure.

[b] Change is the calculated difference from Baseline to End.

symptoms [Fang et al., 1998]. No relevant differences in temperature and humidity were observed. The rationale behind the chosen exposures was that sham served as a control for the UMTS exposures. If an effect was observed at the UMTS exposure, the two other exposure types could be used to judge which feature of the signal was the important one, if any. In the statistical consideration, it was decided to only include the extra exposures if significant results on the primary hypothesis were found. In lack of significance, the two extra exposures were not considered further in this article.

Non-specific symptoms [Chia et al., 2000; Koivisto et al., 2001; Sandström et al., 2001; Al-Khlaiwi and Meo, 2004; Oftedal et al., 2007] and performance in various cognitive tasks [Podd et al., 1995; Crasson et al., 1999; Koivisto et al., 2000; Edelstyn and Oldershaw, 2002; Haarala et al., 2003; Haarala et al., 2004] have been used as a tool to assess EMF effects related to mobile phones. Unfortunately, most of the experiments investigating effects on human well-being and cognitive processing are difficult to compare, not only in terms of field intensity, but also other factors such as sample size, exposure technique and length of exposure, different cognitive tests, analysis and outcome. Moreover, observed effects associated with exposure to mobile phone-related EMF cannot be compared with those observed from phone base stations, since the fields from the base-stations are considerably smaller than those from mobile phones and are probably due to other mechanisms, that is, escalating temperatures, which is not the case in the base station.

The very few similar experimental studies of mobile phone base station radiation also present conflicting findings. Zwamborn et al. [2003] showed that EMF from base stations increases reported subjective symptoms, a finding which was not confirmed in the replication study by Regel et al. [2006]. In that study also, no consistent effect on cognitive performance was reported. This is in congruence with the results by Zwamborn et al. [2003] who also reported no effect by UMTS exposure on cognitive performance. The results from the present study are not strictly comparable since this was not a replication study. In the two above-mentioned studies, participants included both healthy participants and self reported electromagnetic hypersensitivity (EHS) participants. These individuals claimed to be hypersensitive to EMF and the term EHS relates to the participants attributing health symptoms to an exposure to EMF [Seitz et al., 2005]. The focus in this study was only on healthy participants, and adolescents were included as they may be more sensitive than adults.

Generally, our results did not confirm our primary hypothesis that UMTS radiation reduces general performance in the TMB test. However, the observed differences, the near-significant finding in the comparison of adults versus adolescents, and the findings on ‘headache’ and ‘concentration difficulties’ warrant further investigation. The use of mobile phones and related technologies will continue to increase in the foreseeable future, and due to the constantly changing technology there is a need for continued research. Our results only allow us to draw conclusions about the acute effects of short-term UMTS base station exposure on symptoms and cognitive function. Further research with particular focus on adolescent or perhaps even younger groups is suggested.

## REFERENCES

Al-Khlaiwi T, Meo SA. 2004. Association of mobile phone radiation with fatigue, headache, dizziness, tension and sleep disturbance in Saudi population. Saudi Med J 25(6):732–736.

Andersen JB, Pedersen GF. 2004. Stråling fra Mobilmaster—et teknisk responsum. Aalborg Universitet [In Danish]. Available online: http://www.tekno.dk/pdf/mobilhoeringbilag.pdf.

Chia SE, Chia HP, Tan JS. 2000. Prevalence of headache among handheld cellular telephone users in Singapore: A community study. Environ Health Perspect 108(11):1059–1062.

Crasson M, Legros JJ, Scarpa P, Legros W. 1999. 50 Hz magnetic field exposure influence on human performance and psychophysiological parameters: Two double-blind experimental studies. Bioelectromagnetics 20:474–486.

Edelstyn N, Oldershaw A. 2002. The acute effects of exposure to the electromagnetic field emitted by mobile phones on human attention. Cogn Neurosci Neuropsychol 13(1):119–121.

Eltiti S, Wallace D, Ridgewell A, Zougkou K, Russo R, Sepulveda F, Mirshekar-Syahkal D, Rasor P, Deeble R, Fox E. 2007. Environmental Health Perspectives. doi:10.1289/ehp. 10286 (available at http://dx.doi.org/). Online 25 July 2007.

European Medicine Agency. 2002. ICH Topic E6 (R1). Guideline for Good Clinical Practice. London, UK. Available online: www.emea.eu.int/pdfs/human/ich/013595en.pdf.

Fang L, Clausen G, Fanger PO. 1998. Impact of temperature and humidity on the perception of indoor air quality. Indoor Air 8: 80–90.

Feychting M, Ahlbom A, Kheifets L. 2005. EMF and health. Annu Rev Public Health 26:165–189.

Gade A, Mortensen EL. 1984. The influence of age, education, and intelligence on neuropsychological test performance. Paper presented at the 3rd Nordic Conference in Behaviour Toxicology, Aarhus, Denmark, 1984.

Haarala C, Björnberg L, Ek M, Laine M, Revonsuo A, Koivisto M, Hämäläinen H. 2003. Effect of a 902 MHz electromagnetic field emitted by mobile phones on human cognitive function: A replication study. Bioelectromagnetics 24:283–288.

Haarala C, Ek M, Björnberg L, Laine M, Revonsuo A, Koivisto M, Hämäläinen H. 2004. 902 MHz mobile phone does not affect short term memory in humans. Bioelectromagnetics 25:452–456.

Hutter HP, Mashammer H, Wallner P, Kundi M. 2006. Subjective symptoms, sleeping problems, and cognitive performance in subjects living near mobile phone base stations. Occup Environ Med 63:307–313.

Keetley V, Wood A, Sadafi H, Stough C. 2001. Neuropsychological sequelae of 50 Hz magnetic fields. Int J Radiat Biol 77(6): 735–742.

Kheifets L, Repacholi M, Saunders R, van Deventer E. 2005. The sensitivity of children to electromagnetic fields. Pediatrics 116(2):303–313.

Koivisto M, Revonsuo A, Krause C, Haarala C, Sillanmäki L, Laine M, Hämäläinen H. 2000. Effects of 902 MHz electromagnetic field emitted by cellular telephones on response times in humans. Cogn Neurosci Neuropsychol 11(2):413–415.

Koivisto M, Haarala C, Krause CM, Revonsuo A, Laine M, Hämäläinen H. 2001. GSM phone signal does not produce subjective symptoms. Bioelectromagnetics 22:212–215.

Lass J, Tuulik V, Ferenets R, Riisalo R, Hinrikus H. 2002. Effects of 7 Hz-modulated 450 MHz electromagnetic radiation on human performance in visual memory tasks. Int J Radiat Biol 78(10):937–944.

Lezak MD, Howieson DB, Loring DW. 2004. Neuropsychological assessment. 4th edition. United Kingdom: Oxford University Press.

Maier R, Greter SE, Maier N. 2004. Effects of pulsed electromagnetic fields on cognitive processes—A pilot study on pulsed field interference with cognitive regeneration. Acta Neurologica Scandinavica 110:46–52.

Oftedal G, Wilén J, Sandström M, Hansson Mild K. 2000. Symptoms experienced in connection with mobile phone use. Occup Med 50(4):237–245.

Oftedal G, Straume A, Johnsson A, Stovner LJ. 2007. Mobile phone headache: A double blind, sham-controlled provocation study. Cephalalgia 27(5):447–455.

Podd JV, Whittington CJ, Barnes GR, Page WH, Rapley BI. 1995. Do ELF magnetic fields affect human reaction time? Bioelectromagnetics 16:317–323.

Preece AW, Iwi G, Davies-Schmidt A, Wesnes K, Butler S, Lim E, Varey A. 1999. Effect of a 915-MHz simulated mobile phone signal on cognitive function in man. Int J Radiat Biol 75(4):447–456.

Regel SJ, Negovetic S, Röösli M, Berdiñas V, Schuderer J, Huss A, Lott U, Kuster N, Achermann P. 2006. UMTS base station-like exposure, well being and cognitive performance. Environ Health Perspect 114(8):1270–1275.

Roosli M, Rapp R, Braun-Fahrlander C. 2003. Radio and microwave frequency radiation and health—An analysis of the literature [In German]. Gesundheitswesen 65(6):378–392.

Sandström M, Wilén J, Hansson Mild K. 2001. Mobile phone use and subjective symptoms. Comparison of symptoms experienced by users of analogue and digital mobile phones. Occup Med 51:25–35.

Seitz H, Stinner D, Eikmann Th, Herr C, Röösli M. 2005. Electomagnetic hypersensitivity (EHS) and subjective health complaints associated with electromagnetic fields of mobile phone communication—A literature review published between 2000 and 2004. Sci Total Environ 349:45–55.

Tombaugh TN. 2004. Trail Making Test A and B: Normative data stratified by age and education. Arch Clin Neuropsychol 19: 203–214.

Warrington EK. 1984. Recognition memory test. United Kingdom: Windsor.

Zwamborn APM, Vossen SHJA, van Leersum BJAM, Ouwens MA, Makel WN. 2003. Effects of Global Communication system radio-frequency fields on Well Being and Cognitive Functions of human subjects with and without subjective complaints. Netherlands Organisation for Applied Scientific Research (TNO). FEL-03-C148 (2003). http://home.tiscali.be/milieugezondheid/dossiers/gsm/TNO_rapport_Nederland_sept_2003.pdf.