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Effects of 2G and 3G Mobile Phones on Performance and Neurophysiology in Adolescents, Young Adults and Older Adults

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Abstract

Objective:

This study was conducted to examine sensory and cognitive processing in adolescents, young adults and older adults, when exposed to 2nd (2G) and 3rd (3G) generation mobile phone signals.

Methods:

Tests employed were the auditory oddball and the N-back. Forty-one 13-15 year olds, forty-two 19-40 year olds and twenty 55-70 year olds were tested using a double-blind cross-over design, where each participant received Sham, 2G and 3G exposures, separated by at least 4 days.

Results:

Accuracy was not affected by exposure overall, but an augmented N1 was found in the 2G condition (independent of age group). The combined groups performed less accurately on the N-back during the 3G exposure (compared to Sham), with post hoc tests finding this effect in the adolescents only. No effect of 2G exposure on N-back was found either overall or in any group separately, and no effect of 2G or 3G exposure was found on reaction time. Neurophysiological underpinnings (event-related alpha; ERA) of the 3G behavioural effects were also affected, with more early ERA and slower late ERA in the 3G (compared to Sham).

Conclusion/Significance:

Employing tasks tailored to each individual's ability level, this study provides support for an effect of acute 3G exposure on human cognitive function.

Key Words: GSM900, W-CDMA, Acute Exposure, EEG, Sensory Processing, Cognitive Processing, Adolescents, Elderly

Introduction

Mobile phones (MPs) transmit and receive signals via electromagnetic fields (EMFs) that are partly absorbed by the MP user. As MPs are commonly used in close proximity to the head, this feature has led to concerns about possible adverse effects on human health. However, principal independent reviews have concluded that there is presently no substantiated evidence of a negative impact on health (WHO, 2006; Challis, 2007; SCENIHR 2009). These groups, though, also argued for the importance of addressing this issue in children (WHO, 2006; Challis, 2007). This is because there is limited research in this area, and there may be substantial differences between adults and children. For example, as the child and adolescent years are critical periods for brain and cognitive development (Yurgelun-Todd 2007), there is the possibility that this may make them more vulnerable to small stressors (Romeo and McEwen, 2006). There have also been some reports suggesting that children and adolescents may absorb more EMF than adults due to their different physical characteristics (de Salles et al., 2006). However, current research suggests that differences between children and adults are likely to be slight compared to the variances observed within the study (Wiart et al., 2008).

Although there is presently no direct link between any adverse health consequences and MP-related EMFs, the situation is quite different when it comes to effects that do not necessarily relate to health. For example, there are now relatively consistent reports of mobile phones affecting the human electroencephalogram (EEG), increasing spontaneous resting alpha (circa 8-13 Hz) power (e.g. Curcio et al., 2005; Croft et al., 2008). However, the functional significance of this is not easily discerned, as increased waking

alpha has been associated with mental idling and attenuation of mental effort (Niedermeyer and Lopes da Silva, 1987), but also with attentional and active inhibitory processes (Klimesch et al., 2000). For instance, Cooper et al. (2003) demonstrated that once the direction of attention was controlled for, alpha power increased with task difficulty during both internally and externally directed attention. Therefore, the alpha findings might be an indication of either a useful or a detrimental effect, and it is important to employ measures with less ambiguity in order to determine the functional significance of any MP-related changes to neural function.

Measures of auditory processing have clear face validity, and their relation with MP-exposure has not been adequately determined. At perhaps the most basic level, auditory thresholds have not been consistently altered by MP exposure. For example, Maier et al. (2004) reported performance decrements in an auditory threshold task after 50-minutes of MP-exposure, which was limited due to its small sample size (N=11), whereas Uloziene et al. (2005), Parazzini et al. (2007) and Cinel et al. (2007) all failed to identify any MP effects on measures of auditory threshold. In terms of EEG measures of neural processes relating to audition, there is again no consistency. For example, three studies reported MP-related changes in event-related spectral power, but these were in different directions and frequencies (increase in 18.75Hz to 31.25Hz, Eulitz et al., 1998; decrease in 1-4Hz and increase in 8-12Hz, Croft et al., 2002; changes in 4-8Hz and 15Hz, Krause et al., 2006). Similarly, although there was consistency in event-related potential (ERP) research in that reduced N1 amplitude and latency was found by both Hamblin et al. (2004) and Maby et al. (2004), Hamblin et al. (2006) were not able to replicate those

results with a stronger research design that had the added benefit of double-blinding, and this lack of effect was replicated by Kleinlogel et al. (2008). Further, a very recent study did not find any MP-effect on mismatch negativity (an ERP index of auditory pre-attentive change detection) (Kwon et al., 2009). Given that these previous studies have reported inconsistent findings, it is important to further examine whether MP-related EMF affects auditory neural activity, especially in adolescents.

Another measure with strong face validity and whose relation to MP-exposure has not been adequately determined is the N-back task. To date, several studies have tested for acute MP effects on cognition using the N-back task. Koivisto et al. (2000) reported a MP-related decrease in reaction time only in the 3-back task (a very difficult version of the task), whereas Regel et al. (2007) reported a similar result but in the 1-back task and with increasing field intensity. However, the majority of MP studies did not report any effects on N-back performance (e.g. Krause et al., 2000a, 2007; Haarala et al., 2003, 2004, 2007). To date, only one group has used EEG measures to test whether there are MP-effects on neural processes relating to subtle cognitive processing during N-back tasks, with no consistency of results. Krause et al. (2000b) reported MP-related alterations in event-related responses within the alpha (8-12Hz) frequency band, whereas they only reported changes in the 6-8Hz and 8-10Hz bands in a more recent study (2007). Chance, individual differences in performance and floor/ceiling effects might all relate to these mixed findings, and it is important to ensure that such factors are accounted for in subsequent research.

Corresponding to this, the present study was designed to examine MP bioeffects in adolescents (13-15 years), young adults (19-40 years), and in an older age group (55-70 years; hereafter 'elderly'). In particular: 1/ It employed an auditory oddball ERP task tailored to individual auditory discrimination thresholds (to reduce error variance due to differences in individuals' difficulty levels). As well as reaction time and accuracy data, this task provides indices of early auditory processing (N1 component of the ERP), as well as later cognitive processing (P3b) and the brain's response to novel 'attention-grabbing' stimuli (P3a). 2/ It employed an N-back task tailored to each individual's ability level to ensure that it was 'difficult but achievable' for each individual (again to reduce error variance and Type II error). As well as reaction time and accuracy data, this task provides an index of event-related alpha power during the cognitive processing.

Further to this, it should be noted that the majority of MP studies have only employed 2nd generation (2G) MPs, with less research conducted on the effect of the newer 3rd generation (3G) MPs on cognitive/sensory processing. It is thus important to examine MP bioeffects with 3G exposures, particularly given that different technologies utilise different frequency ranges. Most 2G phones use the Global System for Mobile (GSM) communication standard, which pulses 890-960 MHz and 1710-1880 MHz (GSM900 and GSM1800 respectively) signals at 217 Hz, whereas most 3G phones use the Universal Mobile Telecommunication System (UMTS), W-CDMA air interface standard, which operates at a higher frequency range of 1900-2170 MHz and is without periodic pulsed modulation content. There is evidence that the frequency composition of the signal may be important for MP-related bioeffects. For example, in terms of sleep EEG, it has been

reported that pulsed but not continuous radiofrequency (RF) increases aspects of the sleep EEG (e.g. Huber et al., 2002; Regel et al., 2007). This study will thus test for effects of 2G and 3G exposures on cognitive processing separately, for adolescents, young adults and the elderly.

Materials and Methods

Participants

Forty-one adolescents (13-15 years, mean = 14.1, St. Dev. =0.87, 21 male), 42 young adults (19-40 years, mean = 24.5, St. Dev. = 4.51, 21 male) and 20 elderly (55-70 years, mean = 62.2, St. Dev. = 3.94, 10 male) healthy volunteers participated in this experiment. Participants were excluded if they were smokers or reported any of the following: hearing problems, current use of psychiatric medication, personal or familial history of psychiatric disorders, history of substance abuse, or history of head injury. The study was approved by the Human Research Ethics Committee, Swinburne University of Technology, and written informed consent was obtained from all participants.

Procedure

A double-blind, partially counter-balanced (complete counterbalancing was lost due to participant attrition and data loss) cross-over design was employed. Each participant was tested under three conditions on separate days; Sham (both 2G and 3G were off); 2G (2G on and 3G off), and 3G (3G on and 2G off), and each session was separated by at least 4-days. Order of exposure, and side of exposure (left/right hemisphere) were partially counterbalanced across both subjects and exposure conditions, and randomly assigned

(note that side of exposure was consistent within-subject). To avoid acute effects of caffeine, participants were requested to abstain from caffeinated beverages and alcohol for 24 hours prior to testing. The timing of the testing sessions was constant across all participants and sessions.

Subject testing was conducted at the Brain Sciences Institute (BSI), Swinburne University of Technology, Melbourne, Australia. Upon arrival, participants completed a demographics questionnaire, were fitted with electrophysiological recording apparatus and seated in a comfortable chair in a sound and electromagnetically shielded recording room with their eyes approximately 60cm from the centre of a computer screen. A cradle containing a 2G handset on one side and a 3G on the other side of the head was placed on the head with neither of the phones transmitting.

At the first session, participants performed an auditory frequency discrimination threshold task, to determine the smallest discernable frequency difference for each individual. Following this, participants performed an electrooculographic (EOG) calibration task, practiced the auditory oddball task and the N-back task, and rested for a period while background EEG data were collected, and the Thayer Activation-Deactivation Adjective Check List (AD-ACL; commonly used to determine levels of psychological arousal; Thayer, 1967) was completed. As the resting EEG and Thayer AD-ACL results are reported elsewhere and are beyond the scope of the present paper, they will not be discussed in detail here.

Participants then rested for 2 minutes while the Sham 2G MP was replaced by another 2G MP (either Sham or Active) and the 'Off' 3G MP was set (to either 'On' or 'Off'). 10 minutes later, participants performed the first cognitive task, which contained either the 7-minute auditory oddball task or the 15-minute N-back task (each task started with 1-minute practice, and the order of the tasks was counter-balanced between subjects). 5 minutes after the first cognitive test, participants performed the second cognitive task, which contained either the N-back or auditory oddball task (whichever one was not performed earlier in that session). 5 minutes after the second cognitive test, participants completed a second AD-ACL. Total MP-exposure time was approximately 55 minutes.

The participant then had a 1-minute break while the 2G MP was swapped for a Sham MP and the 3G was set to 'off' (regardless of whether these were already 'on' or 'off'). Five minutes later, a third AD-ACL was administered to the participants, and they were asked if they were aware of the phones' status.

Auditory Tasks

Auditory stimuli were presented to participants using Stim2 software and hardware (Version 4.0), binaurally via two speakers (placed approximately 60cm behind the participant). Stimuli were 80dB SPL, 200ms (including 20ms rise/fall times) sine waves.

Frequency Discrimination Threshold Task - This consisted of blocks of stimuli, with each block containing 10 pairs of tones, and each pair of tones separated by a visual instruction on the screen. The first tone in the pair was always 1000Hz, and the second in the pair

either the same or a higher (e.g. 1005Hz, 1160Hz, 1080Hz) frequency tone. Stimulus onset asynchrony (SOA) ranged from 1400 to 1900ms (mean = 1650ms). Participants were instructed to press "Yes" when the tones were the same and "No" when they were different (on a button box). The frequency difference between the stimuli within each block was governed by the accuracy of the preceding block, such that the difference was halved (minimum decrease of 5Hz) if participants achieved at least 80% accuracy in the preceding block, and was increased (by a minimum of 5Hz, up to a maximum of 40Hz) if they were less accurate than 80%. The smallest possible difference between the two tones in the pair was 5 Hz, and the minimum frequency difference detected (with > 80% accuracy) was used for that participant in the subsequent task. This task concluded when participants obtained > 80% accuracy for a total of six blocks of stimuli.

Auditory Oddball Task - 320 stimuli were presented with a mean SOA of 1500 ms (range 1000-2000 ms). 80 percent were standards (80dB SPL, 200ms, including 20ms rise/fall times, 1000Hz), 10 percent were targets (differing from standards only in terms of frequency, which was determined from the above frequency discrimination threshold task), and 10 percent were 200ms novel tones (designed specifically to be novel and very different to both standards and deviants (e.g. the sound of glass breaking). Participants were instructed to press "Yes" to the high-frequency tones (i.e. oddball tones) and ignore the standard tones and the novel tones. The total length of the task was 7 minutes.

N-back Tasks

For each of the three N-back tasks (1-back, 2-back, and 3-back tasks), there were 90 stimuli (made up of 21 consonants, of which 30 were targets and 60 non-targets). Each stimulus was approximately 2cm wide and 4cm high on the screen, and was presented for 500 ms (SOA = 3000 ms) at the centre of a computer monitor, using Stim2 software and hardware (Version 4.0). Different instantiations of the tasks versions were used for each difficulty level and exposure condition.

Participants were asked to press "Yes" as quickly and accurately as possible to each letter that was the same as the letter 1, 2 or 3 stimuli before (for the 1, 2 or 3-back task respectively), and otherwise to press "No". They were also instructed that they could ignore the case of the letters (which was varied to ensure that the intention rather than instantiation of the letters was used for memory processes).

MP Exposure Set-Up

A Nokia 6110 (pulse modulated at 217 Hz, 894.6 MHz output) test phone was used for the 2G exposure. This was set via manufacturer software to continuously transmit at a mean power output of 250 mW (peak power of 2 W). The speaker was removed and foam was placed over the speaker inside a phone case to ensure that there was no sound audible. Further to this, in all conditions, 50 dB background white noise was continuously generated to produce a consistent ambient noise level.

3G exposure was achieved by a standard (or 'dummy') model of a mobile phone handset, which consisted of a metallic handset approximately the shape and size of a typical

mobile phone, which incorporated a monopole antenna externally fed by an RF signal source capable of simulating a W-CDMA signal. This setup produced no detectable sound or temperature rise in the unit. The 3G model handset was driven with a 1900 MHz 3G modulated signal at 125 mW (average), the nominal maximum average transmit power of 3G mobile phone handsets.

Measurements and computational modelling of specific absorption rate (SAR) were conducted to determine induced SAR. Measurements to determine the maximum peak spatial SAR averaged over 10 g were conducted with a commercial DASY 4^{TM} (DYMSCO, Gyounggi-do, Korea) robotic SAR measurement system using dielectric simulating liquids, phantoms and methods conforming with international SAR measurement standards (IEC 2005). The system employed an immersible miniature electric field probe providing 5 mm spatial resolution. Computer simulations were also performed using commercially available software packages based on finite difference time domain (FDTD) and method of moments (MoM). The FDTD analysis used a heterogeneous Visible Human head (1.5 mm cubic voxels), and the MoM using a homogeneous IEC 2005 compliant SAM phantom head (dielectric properties equivalent to FCC "average brain"[1]). The handset was positioned in the IEC 2005 "tilt" and "touch" positions for both left and right ears. Both software packages provided 10 g averaged SAR results using algorithms based on the methods of IEEE C95.3 (IEEE 2002). Simulation results for FDTD and MoM were similar to measurements for 10 g averaged results. For 2G exposure at 900 MHz, the resulting maximum peak spatial SAR averaged over 10 g was determined to be 0.7 W/kg in the touch position. For 3G exposure at 1900

[1] http://www.fcc.gov/fcc-bin/dielec.sh

MHz, the maximum peak spatial SAR (10 g) was determined to be 1.7 W/kg in the touch position.

For all exposure conditions, two phones were placed in a cradle over the subjects' EEG recording cap, either the 2G phone on the left and the 3G phone on the right temporal areas, or vice versa. The positions of the phones are comparable to normal use (in "touch" position).

EEG Data Acquisition

EEG data were recorded with Neuroscan 4.3.1 acquisition software and SynampsII amplifiers (Compumedics Ltd, Melbourne, Australia), from 61 scalp sites (using a Quickcap), and with 9mm diameter tin electrodes attached at the mastoids, and above and below the left eye and on the outer canthi of the eyes (for recording eye movement). Online, EEG data were recorded in direct-current (DC) mode, were referenced to a point midway between Cz and CPz, and grounded midway between Fz and FPz. At the start of the recordings impedances were below 20kΩ. EEG data were amplified with a gain of 2010 and low pass filter of 500Hz online, with a sampling rate of 2000Hz.

Data Analysis

Auditory Oddball task

Behavioural data measures were defined as percentage correct responses to targets 100-1900ms post stimulus ('Accuracy'), and mean reaction time to correctly identified targets

('RT'). Participants who scored less than 50% accuracy in the Sham condition were excluded from further analyses.

EEG data were decimated to 250Hz, 30Hz low-pass filtered, re-referenced to the average of the two mastoid channels, and EOG corrected ('CB'; Croft et al., 2005). Data were then segmented from 2000ms pre-stimulus to 2000ms post-stimulus, and baseline-corrected (-200ms pre-stimulus to 0ms). Epochs with EEG amplitude at any scalp site exceeding ±150μV in the range 200ms pre-stimulus to 800ms post-stimulus, were rejected. Epochs corresponding to standard tones, oddball tones and novel tones were then averaged separately.

Grand Mean averages across the three exposure conditions were created for each age group separately. From these averages, peak latencies for relevant ERP components were then obtained in each age group separately (within the 50-150 ms range for N1, 200-400 ms range for P3a, and 300-500 ms range for P3b), and these were subsequently used to determine time-windows for automatically detecting peaks in the individuals' averaged waveforms: N1 components were detected from each individual's averaged waveform to the standard tones at C3, Cz and C4 electrodes of each age group (with the detection time-windows set at the Grand Mean peak latency +/-30 ms). P3b component was detected from the averaged waveforms to the oddball tones at P3, Pz, P4 electrodes of each age group (with the detection time-windows set at the Grand Mean peak latency +/-150 ms). P3a was detected from the averaged waveforms to the novel tones at F3, Fz, F4 electrodes of each age group (with the detection time-windows set at the Grand Mean

peak latency +/-70 ms). The automatically detected peaks from each individual averaged waveform were then visually inspected and adjusted where maximum/minimum points rather than peaks had been detected.

N-back task

Behavioural data measures were defined as percentage correct responses to targets 100-2900ms post stimulus ('Accuracy'), and mean reaction time to correctly identified targets ('RT'). For each participant, Accuracy in the Sham condition was used to determine the difficulty level to be used for that individual for the analysis (Optimum). This optimum level was defined as the most difficult n-back level that still resulted in at least 70% accuracy (the participant's data was excluded if they could not achieve at least 50% accuracy in at least one of the n-back levels). This means that the EMF comparisons only involved one of the n-back levels (1, 2 *or* 3-back), and that the particular level was different for different participants (but consistent within individual across exposure conditions).

EEG data from each participant's 'optimal' task were decimated to 250Hz, 30Hz low-pass filtered, re-referenced to common average, and EOG corrected (Croft et al., 2005). Data were then segmented from 2500ms pre-stimulus to 3000ms post-stimulus, and baseline-corrected (-1000ms pre-stimulus to 0ms). Epochs with EEG amplitude at any scalp site exceeding ±200μV in the range 1000ms pre-stimulus to 1000ms post-stimulus, were rejected. The event-related alpha (ERA: 8-13Hz) corresponding to non-target

stimuli were then averaged, using the Neuroscan Edit 4.3 'ERBP' function (i.e. it combined both phase-locked and non-phase-locked components of the signal).

Spatial singular value decomposition (SVD; equivalent to spatial principal component analysis without rotation of components) was employed to separate ERA components as there is not the degree of knowledge regarding these as there are for ERP components. SVD identified 2 components in the grand average ERA data (a negative peak at 100 ms and a positive peak at 550 ms, which together accounted for 95% of the data variance). Using these component loadings, waveforms were then recomposed for each condition and participant separately, and peak amplitudes and latencies of these components detected within the ranges 50-200 ms and 150-750 ms respectively.

Results

MP Status

As reported in Croft et al. (submitted), overall there was a tendency for each of the groups to report that the phone was more likely to be on than off, but this was independent of exposure status ($Z[19\text{-}39]<1.55$; $p>0.121$). The strongest of these non-significant findings was for the elderly group, who incorrectly reported that the Sham was actually an active exposure (when compared with the 3G condition).

Auditory Oddball

Two participants were excluded from the performance and P3b analyses due to poorer than 50% Accuracy in the Sham condition. Accuracy scores were transformed to improve normality using the square root function.

To determine whether there were any MP effects on participants' performance, planned mixed design contrasts (ANOVA) were performed, comparing Sham to each of 2G and 3G separately, as well as the interaction of these with Group, where 1/ 'Accuracy' and 2/ 'Reaction time' were the dependent variables.

Accuracy did not differ between Sham and either 2G ($F[1,96]=0.41$, $p=0.527$) or 3G ($F[1,96]=1.05$, $p=0.309$), and these did not interact with Group ($F[1,96]=1.56$, $p=0.216$ and $F[1,96]=2.77$, $p=0.068$, respectively). To explore the trend-level interaction with the 3G/Sham contrast, follow-up analyses were performed for each age group separately, where no effect of exposure was found in the adolescents or elderly ($F[1,38]=0.64$, $p=0.430$ and $F[1,18]=0.14$, $p=0.708$, respectively), but reduced accuracy was found in the young adults ($F[1,40]=7.12$, $p=0.011$; compared to a corrected alpha of 0.017). This suggests that there may be reduced accuracy in the young adults. RT did not differ between Sham and either 2G ($F[1,96]=0.17$, $p=0.682$) or 3G ($F[1,96]=0.51$, $p=0.477$), and these did not interact with Group ($F[1,96]=0.13$, $p=0.881$ and $F[1,96]=0.75$, $p=0.475$, respectively). (See Table 1a for descriptive statistics of the auditory behavioural data.)

To determine whether there were any MP effects on participants' ERP components, planned mixed design contrasts (ANOVA) were performed, comparing Sham to each of

2G and 3G, as well as the interaction of these with Laterality (ipsilateral - contralateral), Group, and Laterality X Group, for each of: 1/ N1 peak amplitude; 2/ N1 peak latency; 3/ P3a peak amplitude; 4/ P3a peak latency; 5/ P3b peak amplitude; and 6/ P3b peak latency.

N1 amplitude was larger in the 2G than Sham condition ($F[1,98]=4.39$, $p=0.039$), and this did not interact with Group ($F[2,98]=0.61$, $p=0.547$), Laterality ($F[1,98]=0.01$, $p=0.940$), or Group X Laterality ($F[2,98]=2.38$, $p=0.098$). N1 did not differ between Sham and 3G ($F[1,98]=0.43$, $p=0.516$), nor did this interact with Group ($F[2,98]=1.66$, $p=0.195$), Laterality ($F[1,98]=0.17$, $p=0.678$) or Group X Laterality ($F[2,98]=0.70$, $p=0.502$). N1 latency did not differ between Sham and either the 2G ($F[1,98]=0.20$, $p=0.655$) or 3G condition ($F[1,98]=0.50$, $p=0.483$), and these did not interact with Group ($F[2,98]=1.87$, $p=0.160$, and $F[2,98]=0.60$, $p=0.548$, respectively), Laterality ($F[1,98]=0.45$, $p=0.505$ and $F[1,98]=1.96$, $p=0.164$, respectively), or Group X Laterality ($F[2,98]=0.15$, $p=0.863$ and $F[1,98]=1.82$, $p=0.168$, respectively). (See Table 1b for descriptive statistics of the auditory N1 data.)

P3a amplitude did not differ between Sham and either the 2G ($F[1,98]=0.19$, $p=0.664$) or 3G condition ($F[1,98]=0.63$, $p=0.429$), and these contrasts did not interact with Group ($F[2,98]=0.75$, $p=0.475$, and $F[2,98]=0.48$, $p=0.619$, respectively), Laterality ($F[1,98]=0.03$, $p=0.861$ and $F[1,98]=0.45$, $p=0.504$, respectively), or Group X Laterality ($F[2,98]=0.73$, $p=0.484$ and $F[1,98]=1.59$, $p=0.209$, respectively). P3a latency did not differ between Sham and either the 2G ($F[1,98]=0.07$, $p=0.789$) or 3G condition

(F[1,98]=2.50, p=0.117), and these contrasts did not interact with Group (F[2,98]=2.42, p=0.094, and F[2,98]=0.53, p=0.593, respectively), Laterality (F[1,98]=0.68, p=0.410 and F[1,98]=0.07, p=0.793, respectively), or Group X Laterality (F[2,98]=0.21, p=0.809 and F[1,98]=0.17, p=0.856, respectively). (See Table 1c for descriptive statistics of the auditory P3a data.)

P3b amplitude did not differ between Sham and either the 2G (F[1,96]=1.00, p=0.321) or 3G condition (F[1,96]=0.24, p=0.624), and these contrasts did not interact with Group (F[2,96]=0.43, p=0.655, and F[2,96]=0.47, p=0.627, respectively), Laterality (F[1,96]=0.13, p=0.717 and F[1,96]=3.33, p=0.071, respectively), or Group X Laterality (F[2,96]=0.37, p=0.691 and F[1,96]=0.69, p=0.505, respectively). P3b latency did not differ between Sham and either the 2G (F[1,96]=0.64, p=0.426) or 3G condition (F[1,96]=0.01, p=0.925), and these contrasts did not interact with Group (F[2,96]=0.58, p=0.565, and F[2,96]=0.61, p=0.547, respectively), Laterality (F[1,96]=0.70, p=0.406 and F[1,96]=0.26, p=0.609, respectively), or Group X Laterality (F[2,96]=0.09, p=0.912 and F[1,96]=0.09, p=0.918, respectively). (See Table 1d for descriptive statistics of the auditory P3b data.)

N-back task

Two participants were excluded from subsequent analyses due to poorer than 50% Accuracy for each of the 3 difficulty levels in the Sham condition. Six participants' ERA data was excluded due to technical issues. ERA Late Component amplitudes were transformed to improve normality using natural log.

To determine whether there were any MP effects on participants' performance, planned mixed design contrasts (ANOVA) were performed, comparing Sham to each of 2G and 3G separately, as well as the interaction of these with Group, where 1/ 'Accuracy' and 2/ 'Reaction time' were the dependent variables.

Accuracy was better in Sham than 3G ($F[1,98]=4.31$, $p=0.041$), and this finding interacted with Group ($F[2,98]=5.54$, $p=0.005$). Post hoc analyses found that this effect was significant in the adolescents ($F[1,40]=10.753$, $p=0.002$; compared to the adjusted p-value of 0.017) but not the young adults ($F[1,39]=2.14$, $p=0.152$) or elderly ($F[1,19]=1.29$, $p=0.270$). Accuracy did not differ between Sham and 2G ($F[1,98]=1.05$, $p=0.309$), nor did this contrast interact with Group ($F[2,98]=0.15$, $p=0.857$). RT did not differ between Sham and either 2G ($F[1,98]=0.01$, $p=0.931$) or 3G ($F[1,98]=0.15$, $p=0.861$), and these did not interact with Group ($F[1,98]=0.26$, $p=0.615$ and $F[1,98]=0.61$, $p=0.546$, respectively). (See Table 2a for descriptive statistics of the N-back behavioural data.)

To determine whether there were any MP effects on participants' two ERA components, planned mixed design contrasts (ANOVA) were performed, comparing Sham to each of 2G and 3G, as well as the interaction of each of these with Group, for each of: 1/ ERA Early Component peak amplitude; 2/ ERA Early Component peak latency; 3/ ERA Late Component peak amplitude; and 4/ ERA Late Component peak latency.

The amplitude of the early component was larger for 3G than Sham ($F[1,94]=5.18$, $p=0.025$), but this effect did not interact with Group ($F[2,94]=2.09$, $p=0.129$). This amplitude did not differ between 2G and Sham ($F[1,94]=0.13$, $p=0.716$), and this did not interact with Group ($F[2,95]=0.26$, $p=0.769$). The latency of the early component did not differ between Sham and either 2G or 3G ($F[1,94]<1.77$, $p>0.187$), and the Sham/2G contrast did not interact with Group ($F[2,94]=1.29$, $p=0.280$). However, the Sham/3G contrast did interact with Group ($F[2,95]=3.54$, $p=0.033$), and the follow-up analyses found a trend to slower latencies in the Elderly in the 3G compared to Sham ($F[1,18]=4.15$, $p=0.057$; compared to the adjusted p-value of 0.017), but no differences in the Adolescent group or in the Young Adult group ($F[1, 38]<2.07$, $p>0.158$).

The amplitude of the late Component did not differ between Sham and either 2G or 3G ($F[1,93]<1.98$, $p>0.481$), and these contrasts did not interact with Group ($F[2,93]<0.75$, $p>0.477$). The latency of the late component was slower in 3G than in sham ($F[1,94]=4.64$, $p=0.034$), and this did not interact with Group ($F[2,94]=0.17$, $p=0.843$). The latency of the late component did not differ between Sham and 2G ($F[1,94]=0.17$, $p=0.680$), and this did not interact with Group ($F[2,94]=0.27$, $p=0.766$). (See Table 2a for descriptive statistics of the N-back ERA data.)

Discussion

The present study was designed to examine MP bioeffects in adolescents, young adults, and elderly, by employing an auditory oddball ERP task tailored to individual auditory discrimination thresholds, and an N-back task tailored to ensure that it was difficult but

achievable for each individual. This method thus overcomes floor and ceiling effects that can confound research and lead to Type II error (failing to identify real effects).

In terms of the auditory oddball task, participants (all ages combined) did not show any change on their accuracy or reaction time of their response to the target tones, when they were exposed to either 2G or 3G MP. However, when considering the young adults alone, there was a reduction in accuracy of approximately 5% in the 3G condition. It may be argued that this finding is problematic in the sense that the group by exposure condition interaction was only significant at a trend-level, and so it needs to be clarified that this effect (it was significant at the $p=0.05$ level after controlling for the three post hoc comparisons) may or may not be significant depending on how the statistical analyses were planned. However, there was no significant effect on P3b, and as this index is normally thought to represent a more subtle antecedent to the behavioural response, this supports the view that the result in young adults may be due to chance. Participants also did not show any significant 2G or 3G effect on P3a (the ERP response to the novel tones), which is consistent with the null 2G effect on P3a in a previous study (Kleinlogel et al. 2008). Our result suggests that relatively automatic neural responses to novel stimuli were also not affected by either exposure.

The participants overall (combined ages) had a larger N1 in the 2G condition than in the Sham condition. This augmented N1 effect is inconsistent with the reduced N1 (Hamblin et al., 2004; Maby et al., 2004) and the null effect (Kleinlogel et al., 2008; Hamblin et al., 2006) during 2G exposure that has been previously reported, and so it is difficult to

interpret. One possibility is that the difference may be due to the different age groups sampled. However, although there were no significant differences between the age groups, as the largest magnitude of effect was in the same age group that was tested in the above studies (young adults), this possibility does not appear likely. Another possibility is that the greater control of difficulty level in the present study have made the present study more sensitive to detecting an increase in N1 amplitude, but further research is required before it can be concluded that it represents more than just chance.

In terms of the N-back task, participants (as a combined group) performed on average 2.5% less accurately in the 3G condition (compared to the sham condition), and post-hoc tests narrowed this reduced accuracy to the adolescent group only (independently, the young adults and the elderly were not significantly affected by the 3G exposure). The adolescent group showed, on average, an 8.4% performance decrement in the 3G condition compared to the sham condition, suggesting that 3G MP exposure may interact with working memory performance and brain function in the adolescent brain. Underlying this performance decrement, for the combined age groups the amplitude of the early ERA component was significantly larger and the late ERA component was significantly later (on average 43 ms) in the 3G condition (relative to the sham condition), with a trend-level slowing of the early component in the elderly group (when analysed separately). Thus there was a dissociation between the performance and ERA changes in the adolescents that was not present in the young adults or elderly participants. It is not clear why the neurophysiological underpinnings (ERA) were altered in the 3G condition in all groups whereas the cognitive/behavioural measurements were only

affected in the adolescent group. It may be speculated, however, that as the adolescent brain is still heavily undergoing maturational processes (Segalowitz and Davies, 2004; Brem et al., 2006), that the adolescents were less able to compensate for the neurophysiological alterations produced by the 3G exposure. Another possibility is that there were other subtle neurophysiological effects relevant to the task that were not detected with the present methodology, but that may have been more affected by the 3G exposure in the adolescents than the other groups.

This effect of acute 3G exposure is similar to the previous 2G findings reported by Koivisto et al. (2000) and Regel et al. (2007). However, contrary to those findings, we did not find any effects on the n-back task due to the 2G exposure. There are a number of possible reasons for this discrepancy that cannot be clarified with the present data set. For example, the present 2G exposure SAR profile is considerably different to that of Regel et al. (see Loughran et al. 2008 for a discussion of this), and the present paper used component analysis to focus the statistics on the main components of the ERA whereas the other two did not. Further research is thus required to clarify this. A difficulty with determining why the present results do not neatly reproduce earlier reports is that the mechanism for such bioeffects is not known. For example, while there are currently non-thermal (e.g. excitation of molecular kinetics, altered membrane potentials, altered protein conformation or binding to ligands, and demodulation of ELF components; Adair, 2003; Challis, 2005) and thermal (e.g. micro hot spots, and TRP channels that work as thermoreceptors; Talavera et al., 2008) theories, there are difficulties with each of these

and no consensus on the matter. The present study does not shed further light on this important topic.

Science is not currently in a position to conclude as to the functional significance of the early ERA, nor the change to it seen in the 3G condition. The ERA itself is thought to represent event-related changes to thalamo-cortical networks of the brain, and as such the 3G effect might be loosely categorised as representing an alteration to the dynamics of cortical activation (Pfurtscheller, 2001), but as discussed in the introduction, there is no clear functional meaning that we can attach to this alpha activity. However, what is most important in these results is that an augmented early and delayed later ERA was observed. That the consequent performance was impaired in only the adolescents is also important as it means that individual differences need to be accounted for in mobile phone research. This is because age is only one variable that can differentiate participants in such research, and this raises the possibility that there are other differences that may result in heterogeneous outcomes that may cloud results and increase Type II error. Future research may thus benefit from considering other variables that may interact with potential mobile phone-related bioeffects.

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Legends of Figures:

Figure 1:
The N1, P3a and P3b of the Auditory oddball task during the Sham, 2nd and 3rd generation exposures, for the three age groups separately.

Figure 2:
The Early Component and the Late Component of the ERA of the N-back task during the Sham, 2nd and 3rd generation exposures, for the three age groups separately.

Figure 1

Figure 1.

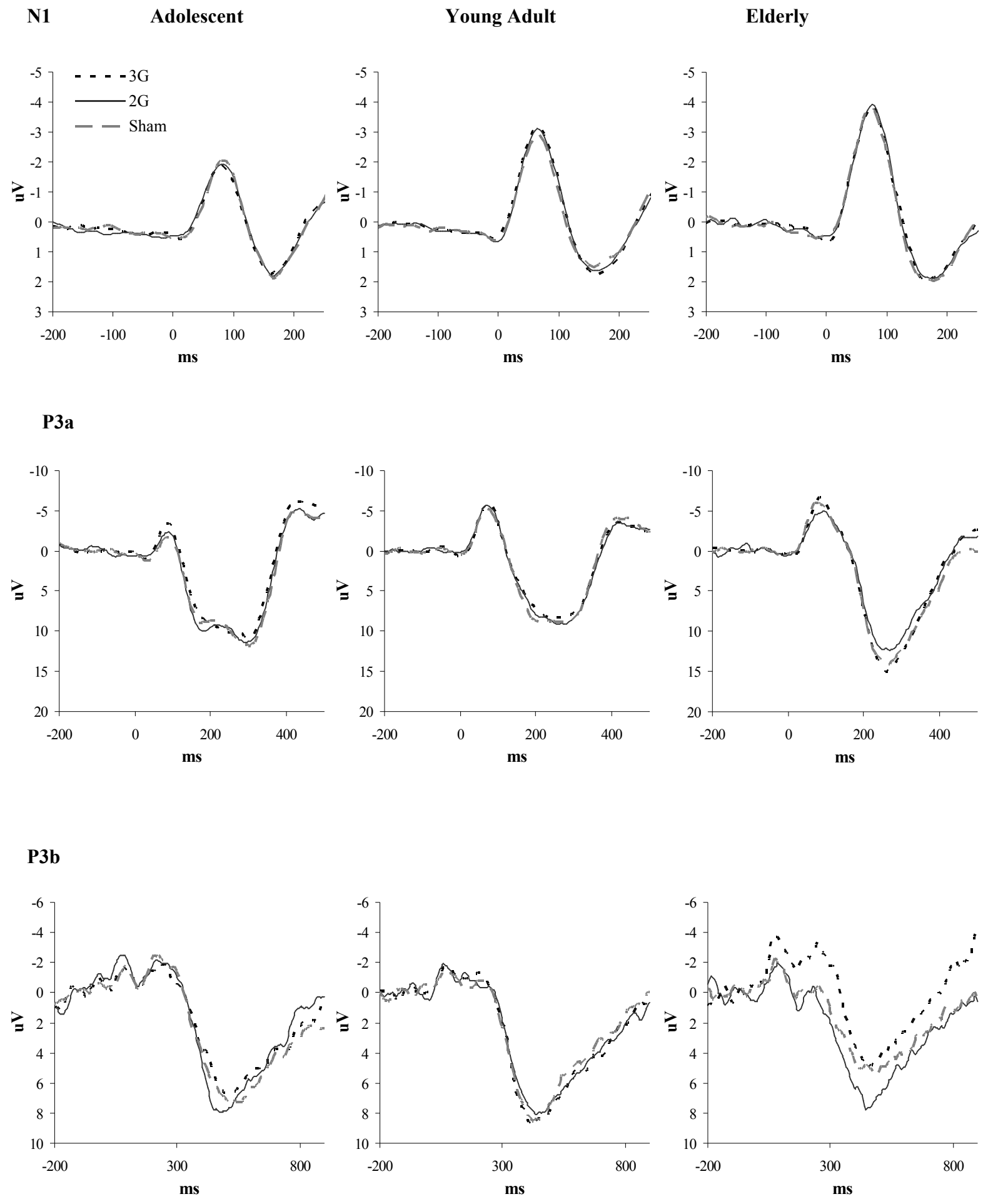
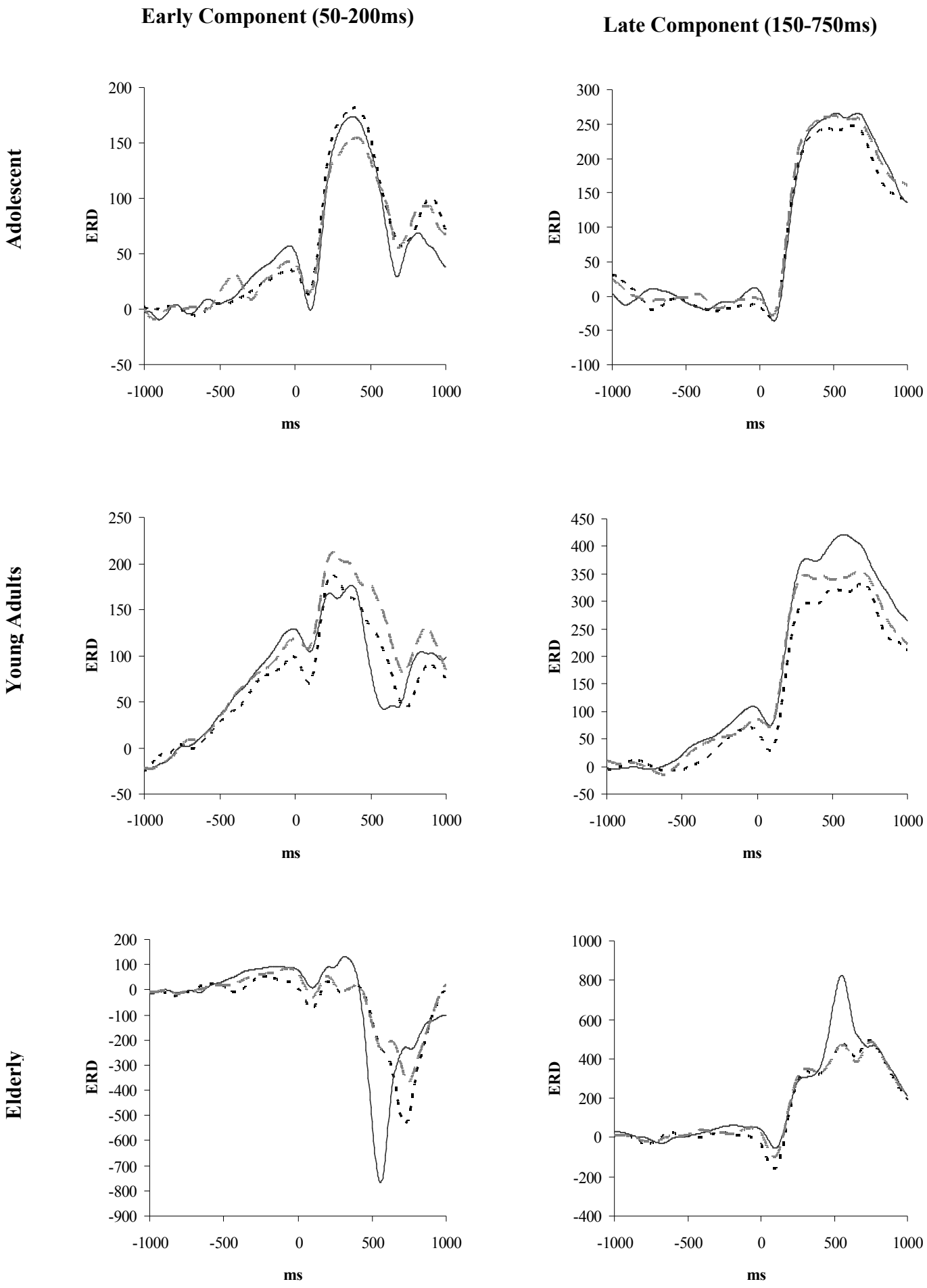


Figure 2.


Early Component (50-200ms)
Late Component (150-750ms)
Adolescent
Young Adults
Elderly
ERD
ms
-1000
-500
0
500
1000

Tables

Table 1a. Auditory oddball task – behavioural data - descriptive statistics

		SHAM		2G		3G	
	GROUP	Mean	SD	Mean	SD	Mean	SD
Reaction Time	**Adolescents**	689.37	101.17	692.06	123.38	694.97	133.57
	Young Adults	565.93	93.04	560.30	77.80	555.65	94.20
	Elderly	560.12	97.40	549.64	89.61	585.18	97.30
Accuracy	**Adolescent**	84.01	14.70	85.95	15.75	84.38	18.06
	Young Adults	91.30	12.42	87.96	18.02	85.44	18.22
	Elderly	92.61	8.54	94.09	8.70	90.66	14.37

The means and standard deviations (SD) of the reaction time and the accuracy are given for the Auditory oddball task during the Sham, 2nd and 3rd generation exposures, for the three age groups separately.

Table 1b. Auditory oddball task – ERP data - N1 descriptive statistics

			SHAM		2G		3G	
	GROUP	**Laterality**	Mean	SD	Mean	SD	Mean	SD
Amplitude	**Adole-scents**	**Contra**	-2.48	1.26	-2.46	1.39	-2.32	1.40
		Cz	-2.41	1.45	-2.40	1.33	-2.30	1.46
		Ipsi	-2.32	1.59	-2.61	1.59	-2.25	1.34
	Young Adults	**Contra**	-2.98	1.31	-3.32	1.66	-3.25	1.63
		Cz	-3.16	1.30	-3.36	1.49	-3.43	1.76
		Ipsi	-2.85	1.25	-3.09	1.21	-3.14	1.61
	Elderly	**Contra**	-3.76	1.48	-4.25	1.58	-3.98	1.04
		Cz	-4.27	1.60	-4.32	1.49	-4.15	1.20
		Ipsi	-3.85	1.60	-4.15	1.51	-3.83	1.29
Latency	**Adole-scents**	**Contra**	88.10	19.13	87.10	15.91	88.10	17.45
		Cz	84.39	18.52	82.00	15.32	82.15	15.34
		Ipsi	88.88	17.17	86.30	16.80	89.85	19.66
	Young Adults	**Contra**	68.76	11.73	68.67	12.74	66.29	15.48
		Cz	66.67	10.37	65.71	11.32	68.29	17.48
		Ipsi	67.14	9.74	67.05	11.27	70.95	15.20
	Elderly	**Contra**	72.21	12.89	77.47	12.52	76.21	10.71
		Cz	71.58	12.14	77.68	11.42	74.74	11.85
		Ipsi	74.74	12.22	78.53	10.09	78.95	13.19

The means and standard deviations (SD) of the amplitude and latency (in units of μV and milliseconds respectively) are presented for the N1 during the Sham, 2nd and 3rd generation exposures, for the three age groups separately, as a function of laterality.

Table 1c. Auditory oddball task - ERP data - P3a descriptive statistics

			SHAM		2G		3G	
	GROUP	**Laterality**	Mean	SD	Mean	SD	Mean	SD
Amplitude	**Adole-scents**	**Contra**	10.01	6.51	10.08	6.98	8.90	6.64
		Fz	15.30	8.55	16.40	8.94	14.56	8.17
		Ipsi	9.75	5.48	10.31	6.28	8.72	6.36
	Young Adults	**Contra**	8.48	4.44	8.61	6.02	7.36	6.38
		Fz	13.25	7.19	12.26	7.82	12.20	7.39
		Ipsi	7.49	5.70	8.54	7.29	7.13	6.06
	Elderly	**Contra**	11.04	5.68	10.50	5.93	12.29	6.17
		Fz	16.01	7.37	14.31	7.13	16.87	8.18
		Ipsi	12.41	6.58	10.78	7.19	11.62	6.33
Latency	**Adole-scents**	**Contra**	276.49	67.08	269.50	64.02	282.05	57.19
		Fz	266.73	58.31	259.00	56.60	272.29	54.28
		Ipsi	275.51	63.56	267.90	62.67	278.73	55.97
	Young Adults	**Contra**	254.19	55.10	267.81	46.14	268.67	52.71
		Fz	248.38	50.22	257.71	45.97	259.14	48.22
		Ipsi	257.24	55.25	266.19	49.59	274.48	48.28
	Elderly	**Contra**	257.68	34.44	261.89	37.93	262.53	34.70
		Fz	259.16	30.74	265.26	36.22	265.89	35.39
		Ipsi	256.42	31.04	257.89	34.78	263.16	34.42

The means and standard deviations (SD) of the amplitude and latency (in units of μV and milliseconds respectively) are presented for the P3a during the Sham, 2nd and 3rd generation exposures, for the three age groups separately, as a function of laterality.

Table 1d. Auditory oddball task - ERP data - P3b descriptive statistics

			SHAM		2G		3G	
	GROUP	**Laterality**	Mean	SD	Mean	SD	Mean	SD
Amplitude	**Adole-scents**	**Contra**	8.50	6.15	9.05	7.67	7.89	9.80
		Pz	10.91	7.92	11.83	8.95	10.92	9.07
		Ipsi	7.61	7.82	7.13	6.97	8.75	8.99
	Young Adults	**Contra**	7.51	4.85	7.72	5.86	7.73	4.89
		Pz	10.98	6.14	10.37	5.74	11.03	6.02
		Ipsi	7.79	5.17	8.27	4.94	8.27	5.04
	Elderly	**Contra**	6.39	6.77	8.16	8.21	3.16	13.42
		Pz	8.51	6.51	9.91	6.07	7.60	8.65
		Ipsi	6.20	5.65	7.86	5.75	5.71	4.93
Latency	**Adole-scents**	**Contra**	514.10	75.73	502.46	79.97	506.20	82.88
		Pz	528.40	78.71	514.36	84.20	516.20	73.32
		Ipsi	500.70	79.68	499.18	76.14	501.90	68.34
	Young Adults	**Contra**	450.34	63.52	448.78	60.05	442.54	66.75
		Pz	445.76	63.09	452.59	69.11	439.61	59.48
		Ipsi	439.90	62.20	448.00	67.69	434.05	61.50
	Elderly	**Contra**	476.84	82.98	460.42	76.17	490.53	63.21
		Pz	476.84	81.90	458.53	75.49	490.32	63.18
		Ipsi	474.11	80.56	458.95	73.75	490.11	61.73

The means and standard deviations (SD) of the amplitude and latency (in units of μV and milliseconds respectively) are presented for the P3b during the Sham, 2nd and 3rd generation exposures, for the three age groups separately, as a function of laterality.

Table 2a. N-back task – behavioural data - descriptive statistics

		SHAM		**2G**		**3G**	
	GROUP	Mean	SD	Mean	SD	Mean	SD
Reaction Time	**Adolescents**	697.16	205.31	686.01	195.95	681.52	184.03
	Young Adults	644.09	174.32	645.38	180.29	652.60	196.42
	Elderly	740.61	212.43	755.29	222.43	774.55	183.48
Accuracy	**Adolescents**	80.33	9.74	79.35	14.27	73.58	14.23
	Young Adults	81.56	9.46	79.17	14.19	83.93	12.76
	Elderly	81.00	8.46	80.17	10.11	77.24	16.72

The means and standard deviations (SD) of the reaction time and the accuracy are given for the N-back task during the Sham, 2nd and 3rd generation exposures, for the three age groups separately.

Table 2b. N-back ERA components descriptive statistics

			SHAM		2G		3G	
		GROUP	Mean	SD	Mean	SD	Mean	SD
Early Component	**Amp**	**Adolescents**	-7.35	129.31	-11.01	161.48	-3.86	142.49
		Young Adults	71.56	155.00	51.12	162.14	37.76	152.45
		Elderly	-53.31	243.58	-46.24	282.60	-142.45	323.64
	Lat	**Adolescents**	96.41	44.40	92.62	34.72	87.59	35.04
		Young Adults	84.00	38.87	95.49	49.38	88.51	40.56
		Elderly	82.53	37.74	94.95	44.94	100.00	50.72
Late Component	**Amp**	**Adolescents**	340.91	153.50	342.95	160.46	324.11	126.96
		Young Adults	449.84	194.69	520.66	330.67	408.69	188.03
		Elderly	850.34	1546.94	1060.71	2208.96	774.45	811.95
	Lat	**Adolescents**	490.67	125.47	516.92	144.45	546.26	146.64
		Young Adults	525.54	173.27	523.59	175.99	560.62	173.60
		Elderly	567.79	169.87	567.79	167.56	600.21	152.62

The means and standard deviations (SD) of the amplitude (Amp) and the latency (Lat) are given for N-back ERA components during the Sham, 2nd and 3rd generation exposures, for the three age groups separately.

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