Available online at www.sciencedirect.com
ScienceDirect
Hormones and Behavior 53 (2008) 503 – 508
Hormones and Behavior
www.elsevier.com/locate/yhbeh

Physiological variation in estradiol and brain function: A functional magnetic resonance imaging study of verbal memory across the follicular phase of the menstrual cycle

Michael C. Craig [a,*], Paul C. Fletcher [b], Eileen M. Daly [a], Janice Rymer [c], Mick Brammer [d], Vincent Giampietro [d], Declan G.M. Murphy [a]

[a] Section of Brain Maturation (PO50), Department of Psychological Medicine, Institute of Psychiatry, Kings College, London, SE5 8AF, UK
[b] Brain Mapping Unit (PO189), Department of Psychiatry, University of Cambridge, CB2 2QQ, UK
[c] Department of Women's Health, St Thomas' Hospital, London, SE1 7EH, UK
[d] Brain Image Analysis Unit (PO89), Centre for Neuroimaging Sciences, Kings College, London SE5 8AF, UK

Received 16 August 2007; revised 2 November 2007; accepted 2 November 2007
Available online 22 November 2007

Abstract

Women frequently complain of memory problems at times in their reproductive lives that are associated with changes in estrogen concentration (e.g. around menopause and childbirth). Further, behavioural studies suggest that memory performance may fluctuate across the menstrual cycle. For example, performance on verbal tasks has been reported to be greatest during phases associated with high estrogen concentrations whereas the opposite has been reported with visuo-spatial tasks. The biological basis of these reported effects remains poorly understood. However, brain imaging studies into the effects of estrogen therapy in postmenopausal women suggest that estrogen modulates the metabolism and function of brain regions sub-serving memory. Furthermore, we have recently reported that acute suppression of ovarian function in young women (with a Gonadotropin Hormone Releasing Hormone agonist) is associated with decreased activation in left prefrontal cortex, particularly the left inferior frontal gyrus (LIFG), during successful verbal memory encoding. We therefore investigated whether physiological variation in plasma estradiol concentration is associated with differences in activity of the LIFG during successful verbal encoding. We hypothesised that higher plasma concentrations of estradiol would be associated with increased brain activity at the LIFG and improved recall performance. Although we did not find a significant relationship between plasma estradiol concentration and verbal recall performance, we report a positive correlation between brain function and estradiol concentration at the LIFG.

Keywords: Estradiol; Menstrual cycle; fMRI; Verbal memory; Left inferior frontal gyrus

Introduction

Women frequently complain of memory problems at times in their reproductive lives that are associated with changes in estrogen concentration (e.g. around the time of the menopause and childbirth) (Mitchell and Woods, 2001). Studies to clarify the possible biological basis of this have generally focussed on the differences between postmenopausal women on and off estrogen therapy (ET), or examined younger women following acute medical or surgical loss of ovarian function. Some of these prior studies reported that verbal, and less consistently visual, memory improved in postmenopausal women taking ET (Jacobs et al., 1998; Kampen and Sherwin, 1994; Maki et al., 2001; Sherwin, 1988; Sherwin and Phillips, 1990; Zec and Trivedi, 2002) (particularly parenteral 17-β estradiol (E2)). Verbal memory deficits have also been reported in women following acute loss of ovarian function, and these deficits have been reversed with estrogen 'add-back' therapy (Newton et al., 1996; Phillips and Sherwin, 1992; Sherwin and Tulandi, 1996; Sherwin and Phillips, 1990). Thus there is increasing evidence that in some women estrogen may affect verbal memory.

* Corresponding author. P050, Institute of Psychiatry, De Crespigny Park, Denmark Hill, London, SE5 8AF, UK. Fax: +44 20 7848 0650.
E-mail address: m.craig@iop.kcl.ac.uk (M.C. Craig).

0018-506X/$ - see front matter © 2008 Published by Elsevier Inc.
doi:10.1016/j.yhbeh.2007.11.005

The biological basis of these effects remains poorly understood. However, brain imaging studies in postmenopausal women reported that ET modulates the metabolism and function of brain regions sub-serving memory (e.g. hippocampal, frontal, parietal, and temporal regions) (Maki and Resnick, 2000; Resnick et al., 1998; Shaywitz et al., 1999). Furthermore, we have recently reported that acute suppression of ovarian function (following administration of a Gonadotropin Hormone Releasing Hormone agonist (GnRHa)) in young healthy women is associated with decreased activation in left prefrontal cortex, and particularly the left inferior frontal gyrus (LIFG), during successful verbal memory encoding (Craig et al., 2007). This finding is consistent with reports of an association between LIFG activation at encoding with subsequent memory success (Buckner et al., 2000; Davachi et al., 2003; Jackson and Schacter, 2004; Ranganath et al., 2003; Staresina and Davachi, 2006). Also it suggests that modulation of LIFG function may be an important mechanism through which estrogen affects verbal memory formation.

Several previous studies have reported that hormonal variation across the menstrual cycle is associated with significant changes in brain activity during motor and language tasks (Dietrich et al., 2001; Fernandez et al., 2003; Goldstein et al., 2005) but we are unaware of any brain imaging studies to date that have analysed the relationship between the normal variation in estradiol levels across the menstrual cycle and brain function during a memory task. This is, however, an area of potential interest as behavioural studies suggest that memory performance may fluctuate across the menstrual cycle. For example, high estrogen levels are associated with improved performance on verbal tasks, whereas improved performance on visuo-spatial tasks is associated with lower estrogen levels (Hampson, 1990a, b; Hoff et al., 2001; Rosenberg and Park, 2002; Young-Hoon et al., 2006). We therefore carried out the first study to investigate whether physiological variation in plasma estradiol concentration is associated with differences in activity of the LIFG during successful verbal encoding. We hypothesised that higher plasma concentrations of estradiol would be associated with increased brain activity at the LIFG and improved recall performance. In order to avoid the potentially confounding effect of changes in progesterone levels, we limited our analysis to the follicular phase of the cycle (i.e. when progesterone levels are low (≤ 8 nmol/l) and estradiol levels are rising).

Methods

Subjects

We included 16 right-handed young (26–45 years) pre-menopausal women with regular menstrual cycles. All women signed informed consent as per the Ethics Committee Guidelines of the University of London.

Exclusion criteria

All the women were screened to exclude psychiatric disorders using the Structured Clinical Interview for DSM-IV Axis I and II Disorders (SCID-I and SCID-II) (First et al., 1997a,b). Scores on the Beck Depression and Anxiety Inventories (BDI and BAI, respectively) (Beck et al., 1988, 1996) were also obtained to quantify sub-clinical symptoms of depression and anxiety. General intelligence and cognitive status were measured using the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) and the Mini Mental State Examination (MMSE) (Folstein et al., 1983). Women were excluded if they: had an IQ less than 70, a MMSE score less than 27, or they were unable to carry out the cognitive tasks we wished to investigate. They were also excluded if they had a history of: alcohol/drug abuse, significant medical/neurological problems affecting brain function, were taking regular prescribed medication (including the contraceptive pill), or did not have regular menstrual cycles. All subjects had routine blood tests prior to the study day to exclude women with significant abnormalities in full blood count; plasma glucose; or liver renal, thyroid, or ovarian function. They also had blood tests on the day of the scan and excluded if their progesterone levels were greater than 8 nmol/l.

Stimulus materials

Stimulus lists were created using nouns randomly selected from the MRC psycholinguistic database (http://www.psy.uwa.edu.au/MRCDataBase/uwa_mrc.htm). Initially two lists were created; a 300-word list composed of 'living' nouns (e.g. apple, liver) and a 300-word list composed 'non-living' words (e.g. chair, mountain). Words ranged in their written frequency of use between 1 and 30 per million (Kucera and Francis, 1967) and were between four and eight letters in length. These lists were then used to create three 100-word encoding lists (A–C) and six 100-word recognition lists. Lists were matched with respect to word length or frequency of use. Encoding lists were made up of 50 words from the 'living' word lists and 50 words from the 'non-living' word list. Each of the two 100-word recognition lists included 50 'old words' from the originally encoded list and 50 'new words' that had not been in the encoded list. The 'new words' included an equal number of 'living' and 'non-living' items. Each of the three encoding lists (A–C) therefore had two associated recognition lists, each made up of 50 'old words' from the encoded list and 50 'new words'. An additional 16 words were selected from the word pool to create a practice list for the study task.

Encoding task

Subjects were asked to decide whether words presented to them represented a 'living' or 'non-living' object by moving a mounted joystick, on their right-hand-side, to the left ('living' object) or right ('non-living' object). They were informed that the purpose of this task was to help them learn the words which they would later be asked to recognise. Women were presented with 100 words, each for a period of 200 ms, with an inter-stimulus interval of 200 ms.

Recognition task

The recognition memory test consisted of the 100 'old-words' that had previously been presented, together with 100 'new-words' (lures) divided into two lists of 100 words presented 5 min apart. For each word, volunteers had to decide whether they had seen the word before during the experiment by moving the mounted joystick, on their right-hand-side, to the left ('old-word') or right ('new-word'). The words were presented in the same manner as in the encoding task.

Stimuli presentation

Each woman was randomly allocated one of the three encoding lists (A–C) and their reciprocal recognition lists. Words were back-projected with an LCD projector (Proxima Desktop Projector 5500) onto a screen 2.5 m from the subject's head in white upper case Times New Roman 48-point font on a black background and were visible to the subject via a prism mounted on the head coil. The paradigms were programmed in Microsoft Visual Basic Professional 6.0 and presented on a PC running MS Windows XP.

Procedure

Before entering the scanner, women were given an explanation about the tasks and undertook a short practice session using a laptop computer to familiarise themselves with the tasks.

Scanning began with a ~20 min structural scan. Volunteers then performed the encoding task which lasted ~10 min. They were then given two unrelated tasks lasting for a period of ~25 min whilst remaining in the scanner. They were

subsequently asked to carry out the forced recognition tasks. Each task lasted ~10 min with a ~5 min delay between tasks.

Experimental paradigm

This study was carried out as part of a larger study into the effects of ovarian steroids on brain function (MCC unpublished data). All women were initially scanned when they were predicted to be in the follicular phase of the menstrual cycle (high estrogen/low progesterone). Blood tests were taken on the day of the scan to confirm hormonal levels.

Blood collection and endocrine determinants

Estradiol and progesterone concentrations were quantified using a competitive immunoassays (supplied by Bayer Advia Centaur) using direct chemiluminometric technology. Luteinising Hormone (LH) and Follicular Stimulating Hormone (FSH) were quantified using two-site sandwich immunoassays (supplied by Bayer Diagnostics Europe) using direct chemiluminometric technology.

Analysis of behavioural data

Encoding

A linear regression analysis between the mean accuracy scores of making a living/non-living judgement during encoding and estradiol concentrations was carried out. The cognitive component measured in performing this task (i.e. whether an object was living or non-living) had a relatively low 'ceiling' and we therefore predicted that the correlation between these variables would not be statistically significant.

Recognition

We calculated recognition success for each subject by subtracting the probability of 'false alarms' (i.e. making false judgements that 'new' words were 'old') from the probability of correct 'hits' (i.e. making correct judgements that 'old' words were 'old'). A linear regression analysis was then carried out between this discrimination measure and estradiol levels. We predicted that discrimination success would increase with estradiol level.

MRI scanning methods

Gradient echo echoplanar imaging (EPI) data were acquired on a neuro-optimised GE Signa 1.5 Tesla system (General Electric, Milwaukee WI, USA) at the Maudsley Hospital, London. Consistent image quality was ensured by a semi-automated quality control procedure. A quadrature birdcage headcoil was used for radio frequency transmission and reception.

For blood oxygen level-dependent (BOLD) imaging, 268 T2*-weighted whole-brain volumes were acquired during each of the encoding and forced recognition paradigms at each of 22 near-axial non-contiguous planes parallel to the intercommissural line (slice thickness = 5 mm; gap = 0.5 mm; TR = 2.0 s; echo time = 40 ms; flip angle = 90°; matrix = 64 × 64). At the same time, a high-resolution gradient echo image of the whole brain was acquired in the inter-commissural plane consisting of 43 slices (slice thickness = 3 mm; gap = 0.3 mm; TR = 3 s; flip angle = 90°; matrix = 128 × 128). This EPI data set provided almost complete brain coverage.

Analysis of fMRI data

Data were analysed with XBAM version 3.4 (Institute of Psychiatry, London, U.K.) on a Sun Workstation (Sun Microsystems Inc. Santa Clara, USA).

fMRI analysis, in its most common forms, requires fitting of a time series model at many thousands of intracerebral voxels in a number of individuals. Most assessments of the significance of the resulting model fits in common use in fMRI analysis use normal theory and the validity of the normality assumption is not often tested. Our 'in house' method of analysis (XBAM) makes no such assumptions. Instead, it uses median statistics to control outlier effects and permutation rather than normal theory based inference. Furthermore, our most common test statistic is computed by standardising for individual difference in residual noise before embarking on second level, multi-subject, testing using robust permutation-based methods. This allows a mixed effects approach to analysis. A recent paper by Thirion et al. (2007) has conducted a detailed analysis of the validity and impact of normal theory based inference in fMRI in large number of subjects (Thirion et al., 2007). They have found substantial deviations from normality in a significant number (22%) of intracerebral voxels using the most common measure of response size (unstandardised beta) used in fMRI analysis. They recommend a mixed effects rather than simple random effects analysis, permutation-based inference, and cluster or parcel level rather than voxel level inference. These recommendations have been implemented in XBAM for the last 8 years and have resulted in the publication of around 200 peer-reviewed papers.

Individual analysis

The data were first realigned (Bullmore et al., 1999a,b) to minimise motion-related artefacts and smoothed using a Gaussian filter (full width half maximum 7.2 mm). Responses to the experimental paradigms were then detected by time series analysis using Gamma variate functions to model the BOLD response. In order to constrain the possible range of fits of physiologically plausible BOLD responses, a constrained fitting procedure (Friman et al., 2003) was used. Following this fitting operation, a goodness of fit statistic was computed at each voxel. This was the ratio of the sum of squares of deviations from the mean intensity value due to the model (fitted time series) divided by the sum of squares due to the residuals (original time series minus model time series). This statistic is called the SSQratio. The percentage change in the BOLD signal at each voxel was also calculated. This was $[(\mathrm{fit}_{max} - \mathrm{fit}_{min})/\text{mean signal intensity}] \times 100$, where fit_{max} and fit_{min} were the maximum and minimum values of the fitted response for the time series in question.

In order to sample the distribution of SSQratio under the null hypothesis that observed values of SSQratio are not determined by experimental design (with minimal assumptions), the time series at each voxel was permuted using a wavelet-based re-sampling method (Breakspear et al., 2003; Bullmore et al., 2001). This process was repeated 20 times at each voxel and the data were combined over all voxels, resulting in 20 permuted parametric maps of SSQratio at each plane for each subject. The same permutation strategy was applied at each voxel to preserve spatial correlational structure in the data during randomisation. Combining the randomised data over all voxels yielded the distribution of SSQratio under the null hypothesis. A test that any given voxel is activated at any required type I error was then carried out by obtaining the appropriate critical value of SSQratio from the null distribution. For example, SSQratio values in the observed data lying above the 99th percentile of the null distribution had a probability under the null hypothesis of $<= 0.01$. It has been shown that this permutation method gives very good type I error control with minimal distributional assumptions (Breakspear et al., 2003; Bullmore et al., 2001).

Group mapping

In order to extend inference to the group level, the observed and randomised SSQratio maps were transformed into standard space by a two-stage process involving first a rigid body transformation of the fMRI data into a high-resolution inversion recovery image of the same subject followed by an affine transformation onto a Talairach template (Brammer et al., 1997). By applying the two spatial transformations computed above for each subject to the statistic maps obtained by analysing the observed and wavelet-randomised data, a generic brain activation map (GBAM) was produced for each experimental condition. The median observed SSQratio over all subjects at each voxel (median values were used to minimise outlier effects) was then tested at each intracerebral voxel in standard space (Talairach and Tournoux, 1988) against a critical value of the permutation distribution for median SSQratio ascertained from the spatially transformed wavelet-permuted data (Brammer et al., 1997). In order to increase sensitivity and reduce the multiple comparison problem encountered in fMRI, hypothesis testing was carried out at the cluster level using a method (Bullmore et al., 1999a,b) initially for structural image analysis, and subsequently shown to give excellent cluster-wise type I error control in both structural and functional fMRI analysis. When applied to fMRI data, this method estimated the probability of occurrence of clusters under the null hypothesis using the distribution of median SSQratios computed from spatially transformed data obtained from wavelet permutation of the time series at each voxel (see above). Image-wise

expectation of the number of false positive clusters under the null hypothesis was set for each analysis at <1. Consequently correction for multiple comparisons was not required, as thresholds were set on an image-wide basis, not a voxelwise basis.

Voxel and cluster level correlations of hormonal level with fMRI responses

The Pearson product-moment correlation coefficients (r) of the SSQratio data for the tasks of interest with the estradiol levels were then computed at each intracerebral voxel in standard (Talairach) space. The null distribution of the correlation coefficients was then computed by permuting the order of the hormone levels and recomputing r 50 times at each voxel and combining the resulting data over all intercerebral voxels. Significant correlations were then identified at the voxel and cluster levels as described above under group mapping with the expectation of false positive correlated clusters set at <1 over the whole brain.

Regression analysis

Brain areas in the LIFG showing a significant linear correlation between BOLD response and estradiol levels (after co-varying for IQ), were further examined by extracting the average fMRI responses (SSQs) and estradiol levels for each individual from each of the areas and performing a linear regression.

Analysis of functional aspects of memory task

Our analyses were limited to studying the BOLD response during stimuli that were successfully encoded (i.e. later remembered) versus those that were subsequently forgotten. This widely used method is known as the 'subsequent memory' or 'Dm' effect (Otten et al., 2001).

Results

Baseline screening tests

The mean age of female volunteers was 39 (range 26 to 45) and all women were in the normal range (mean±SEM) with respect to the mini Mental State Examination (29.46±0.24), verbal IQ (98.50±3.31), performance IQ (99.44±3.30), and full scale IQ (99.88±3.14). The Structured Clinical Interview for DSM-IV Axis I and II Disorders Scores, Beck Depression Inventory (8.38±1.9), and Beck Anxiety Inventory (8.29±2.24) confirmed that women included in the study did not have clinically significant mental health problems. The mean estradiol concentration was 624.67 (±131.37), progesterone level 5.33 (±0.20), luteinising hormone 10.92 (±3.23), and follicular stimulating hormone 7.01 (±2.05).

Behavioural results

Encoding

The mean accuracy of living/non-living responses was 87.7% (SEM=1.7%) and a linear regression analysis did not suggest that estradiol levels accounted for a significant amount of the variance in the accuracy ($p=0.984$).

Recognition

Accuracy was calculated by the discrimination measure Pr [probability of a correct hit (P hit) minus probability of a false alarm (P false alarm)]. The mean discrimination measure was 58.06% (SEM 2.84%). A linear regression analysis did not suggest that estradiol levels accounted for a significant amount of the variance in the discrimination index ($p=0.781$).

fMRI results

As predicted, the Dm effect (i.e. the difference between encoding trials that were subsequently correctly recognised with those that were forgotten) was associated with significantly increased activation in the left inferior frontal gyrus (LIFG).

Furthermore, when we extracted the average fMRI responses (SSQs) at the LIFG and estradiol levels for each individual and fitted a linear regression between these variables, the relationship was highly significant ($F1,14$; $t=3.349$, $p<0.005$) (see Fig. 1).

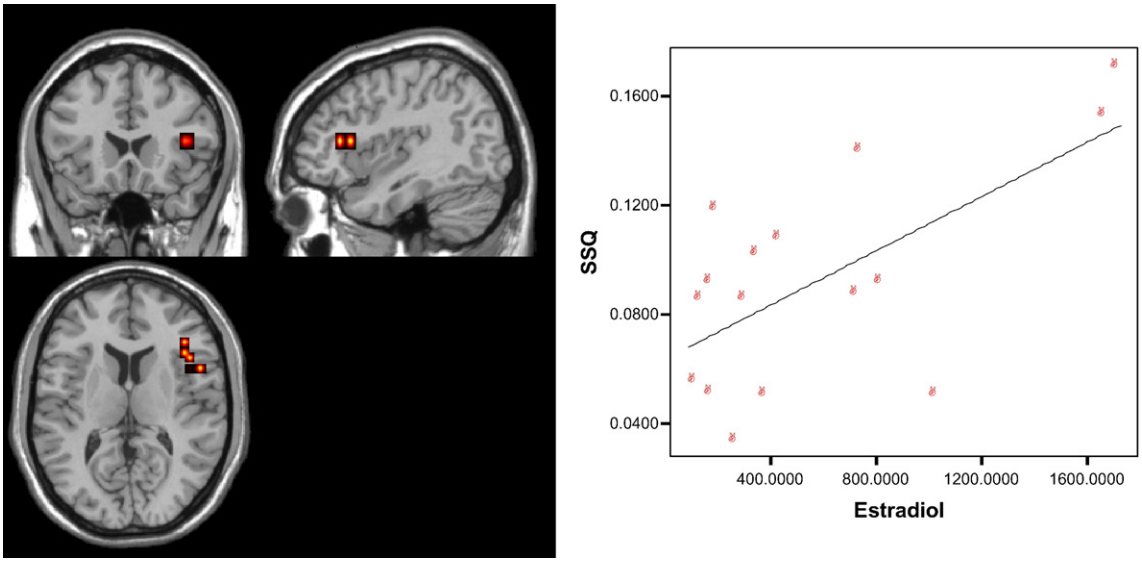

Fig. 1. Correlation of estradiol levels and brain activation (SSQ) at the left inferior frontal gyrus (LIFG). The above figure illustrates the positive correlation between estradiol level and activation (SSQ) at the left inferior frontal gyrus (LIFG) during successful verbal encoding in 16 women.

Discussion

Our aim was to explore the relationship between plasma estradiol concentration and brain function at the left inferior frontal cortex (LIFG) during verbal encoding. We hypothesised that brain function at the LIFG, and verbal memory performance, would be positively correlated with estradiol concentration. In support of this, we report a positive correlation between brain function and estradiol concentration at the LIFG. These preliminary findings are important as they suggest a biological explanation for prior reports that improved verbal memory performance during the normal menstrual cycle is associated with higher estradiol levels.

We did not find a significant relationship between plasma estradiol concentration and verbal recall performance as measured using simple cognitive tests. This finding may be partly due to the fact that results of behavioural tests of memory describe higher order cognitive processing where the outcome measure of a task (e.g. successful verbal memory encoding) is an emergent property of numerous neurofunctional systems working in concert and may not therefore always result in a simple 'one-to-one' relationship between brain and behaviour. Also previous studies have suggested the magnitude of this relationship to be relatively small in the context of relatively small physiological variations of estradiol (see Sherwin, 2003, for review). It is therefore possible that our current study was underpowered to detect a significant behavioural effect—despite having the power to detect changes in the BOLD response at the LIFG.

The focus of this study on the LIFG during verbal encoding was justified *a priori* on the basis of a consistently reported association between brain activity in this region during deep encoding of to-be-learned words and subsequent memory success (Buckner et al., 2000; Davachi et al., 2003; Jackson and Schacter, 2004; Ranganath et al., 2003; Staresina and Davachi, 2006). Furthermore, we had recently found a significant relationship between acute suppression of estrogen (following GnRHa administration) and reduced activation at the LIFG during verbal encoding, associated with reduced recognition success (Craig et al., 2007). However, other studies also suggest that verbal encoding involves activation of a network of brain regions; particularly medial temporal structures (i.e. hippocampus and parahippocampal gyrus) (Buckner et al., 2000). Future research in this area therefore needs to study the interaction between physiological variations in estradiol concentration (i.e. across the menstrual cycle) and a wider network of brain regions. Studies in postmenopausal women suggest that this may yield a more complex picture as ET is associated with increased activity in some regions (e.g. LIFG and hippocampus), but reduced activity in others (e.g. precuneus) (Maki and Resnick, 2000).

Future studies are also required to analyse the mechanisms underlying the interaction between estradiol and memory formation in these brain regions. These mechanisms probably include modulation of neurotransmitter systems associated with learning (see Craig and Murphy, 2007, for review). We have previously reported, for example, that postmenopausal women on long-term ET have significantly greater cholinergic, serotonergic, and dopaminergic responsivity to neuroendocrine challenge tests compared to treatment naive controls (Craig et al., 2004; van Amelsvoort et al., 2001, 2003) suggesting that estradiol may modulate these systems. The cholinergic system has been highlighted as being particularly important in learning and memory (see Hasselmo, 2006, for review), and, in addition to the greater responsivity to cholinergic agonists, animal and human studies have also reported that ET leads to a reduction in the deleterious effects of cholinergic antagonism on memory (Dumas et al., 2006; Fader et al., 1999). Furthermore, we have recently observed an interaction between acute suppression of estrogen (following GnRHa administration) and the cholinergic antagonist scopolamine at the LIFG (not published). This was characterised by a greater attenuation of the relationship between LIFG activity and successful encoding following a scopolamine challenge in women post GnRHa. Taken together, these findings suggest that modulation of the cholinergic system in brain regions important to memory formation, such as the LIFG, is an important mechanism via which estrogen influences learning.

In summary our study suggests that previous reports of a positive association between verbal memory performance and estradiol concentration at different phases of the menstrual cycle may partly be due to the action of estradiol at the LIFG during encoding. Further research is required to determine the precise mechanism(s) through which estradiol affects this modulation.

Acknowledgments

The authors wish to thank Dr. Roy Sherwood and the staff in the clinical biochemistry department at Kings College Hospital for analysing our blood samples, Professor Linda Cardozo for her help in facilitating recruitment at Kings College Hospital, Wyeth Pharmaceuticals for their financial support, and MRC (UK) who funded a Clinical Research Training Fellowship for Dr. Michael Craig.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.yhbeh.2007.11.005.

References

Beck, A.T., Epstein, N., Brown, G., et al., 1988. An inventory for measuring clinical anxiety: psychometric properties. J. Consult. Clin. Psychol. 56, 893–897.

Beck, A.T., Stree, R.A., Brown, G.K., 1996. Beck Depression Inventory, Second edn. The Psychological Corporation Harcourt Brace, San Antonio, TX.

Brammer, M.J., Bullmore, E.T., Simmons, A., et al., 1997. Generic brain activation mapping in functional magnetic resonance imaging: a nonparametric approach. Magn. Reson. Imaging 15, 763–770.

Breakspear, M., Brammer, M., Robinson, P., 2003. Construction of multivariate surrogate sets from nonlinear data using the wavelet transform. Physica. D. 182, 1–22.

Buckner, R.L., Logan, J., Donaldson, D.I., et al., 2000. Cognitive neuroscience of episodic memory encoding. Acta Psychol. 105, 127–139.

Bullmore, E.T., Brammer, M.J., Rabe-Hesketh, S., et al., 1999a. Methods for diagnosis and treatment of stimulus-correlated motion in generic brain activation studies using fMRI. Hum. Brain Mapp. 7, 38–48.

Bullmore, E.T.S., Suckling, J., Overmeyer, S., et al., 1999b. Global, voxel and cluster tests, by theory and permutation, for a difference between two groups of structural MR images of the brain. IEEE Trans. Med. Imag. 18, 32–42.

Bullmore, E., Long, C., Suckling, J., et al., 2001. Colored noise and computational inference in neurophysiological (fMRI) time series analysis: resampling methods in time and wavelet domains. Hum. Brain Mapp. 12, 61–78.

Craig, M.C., Murphy, D.G., 2007. Oestrogen, cognition and the maturing female brain. J. Neuroendocrinol. 19, 1–6.

Craig, M., Cutter, W., Wickhham, H., et al., 2004. Effect of long-term estrogen therapy on dopaminergic responsivity in postmenopausal women. Psychoneuroendocrinology 29, 1309–1316.

Craig, M.C., Fletcher, P.C., Daly, E.M., et al., 2007. Gonadotropin hormone releasing hormone agonists alter prefrontal function during verbal encoding in young women. Psychoneuroendocrinology 32, 1116–1127.

Davachi, L., Mitchell, J.P., Wagner, A.D., et al., 2003. Multiple routes to memory: distinct medial temporal lobe processes build item and source memories. PNAS 100, 2157–2162.

Dietrich, T., Krings, T., Neulen, J., et al., 2001. Effects of blood estrogen level on cortical activation patterns during cognitive activation as measured by functional MRI. NeuroImage 13, 425–432.

Dumas, J., Hancur-Bucci, C., Naylor, M., et al., 2006. Estrogen treatment effects on anticholinergic-induced cognitive dysfunction in normal postmenopausal women. Neuropsychopharmacology 1–14.

Fader, A.J., Johnson, P.E.M., Dohanich, G.P., 1999. Estrogen improves working but not reference memory and prevents amnestic effects of scopolamine on a radial-arm maze. Pharmacol. Biochem. Behav. 62, 711–717.

Fernandez, G., Weis, S., Stoffel-Wagner, B., et al., 2003. Menstrual cycle-dependent neural plasticity in the adult human brain is hormone, task, and region specific. J. Neurosci. 23, 3790–3795.

First, M.B., Spitzer, R.L., Gibbon, M., et al., 1997a. Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-I). American Psychiatric Association, Washington.

First, M.B., Spitzer, R.L., Gibbon, M., et al., 1997b. Structured Interview for DSM-IV Axis II Personality Disorders (SCID-II). American Psychiatric Association, Washington.

Folstein, M.F., Robins, L.N., Helzer, J.E., 1983. The mini-mental state examination. Arch. Gen. Psychiatry 40, 812.

Friman, O., Borga, M., Lundberg, P., et al., 2003. Adaptive analysis of fMRI data. NeuroImage 19, 837–845.

Goldstein, J.M., Jerram, M., Poldrack, R., et al., 2005. Hormonal cycle modulates arousal circuitry in women using functional magnetic resonance imaging. J. Neurosci. 25, 9309–9316.

Hampson, E., 1990a. Estrogen-related variations in human spatial and articulatory-motor skills. Psychoneuroendocrinology 15, 97–111.

Hampson, E., 1990b. Variations in sex-related cognitive abilities across the menstrual cycle. Brain Cogn. 14, 26–43.

Hasselmo, M.E., 2006. The role of acetylcholine in learning and memory. Curr. Opin. Neurobiol. 16, 710–715.

Hoff, A.L., Kremen, W.S., Wieneke, M.H., et al., 2001. Association of estrogen levels with neuropsychological performance in women with schizophrenia. Am. J. Psychiatry 158, 1134–1139.

Jackson III, O., Schacter, D.L., 2004. Encoding activity in anterior medial temporal lobe supports subsequent associative recognition. NeuroImage 21, 456–462.

Jacobs, D.M., Tang, M.X., Stern, Y., et al., 1998. Cognitive function in nondemented older women who took estrogen after menopause. Neurology 50, 368–373.

Kampen, D.L., Sherwin, B.B., 1994. Estrogen use and verbal memory in healthy postmenopausal women. Obstet. Gynecol. 83, 979–983.

Kucera, H.a., Francis, W.N., 1967. Computational Analysis of Present-Day American English. Brown University Press, Providence (RI).

Maki, P.M., Resnick, S.M., 2000. Longitudinal effects of estrogen replacement therapy on PET cerebral blood flow and cognition. Neurobiol. Aging 21, 373–383.

Maki, P.M., Zonderman, A.B., Resnick, S.M., 2001. Enhanced verbal memory in nondemented elderly women receiving hormone-replacement therapy. Am. J. Psychiatry 158, 227–233.

Mitchell, E.S., Woods, N.F., 2001. Midlife women's attributions about perceived memory changes: observations from the Seattle Midlife Women's Health Study. J. Women's Health Gend.-Based Med. 10, 351–362.

Newton, C., Slota, D., Yuzpe, A.A., et al., 1996. Memory complaints associated with the use of gonadotrophin-releasing hormone agonists: a preliminary study. Fertil. Steril. 65, 1253–1255.

Otten, L.J., Henson, N.A., Rugg, M.D., 2001. Depth of processing effects on neural correlates of memory encoding: relationship between findings from across- and within-task comparisons. Brain 124, 399–412.

Phillips, S.M., Sherwin, B.B., 1992. Effects of estrogen on memory function in surgically menopausal women. Psychoneuroendocrinology 17, 485–495.

Ranganath, C., Yonelinas, A.P., Cohen, M.X., et al., 2003. Dissociable correlates of recollection and familiarity within the medial temporal lobes. Neuropsychologia 42, 2–13.

Resnick, S.M., Maki, P.M., Golski, S., et al., 1998. Effects of estrogen replacement therapy on PET cerebral blood flow and neuropsychological performance. Horm. Behav. 34, 171–182.

Rosenberg, L., Park, S., 2002. Verbal and spatial functions across the menstrual cycle in healthy young women. Psychoneuroendocrinology 27, 835–841.

Shaywitz, S.E., Shaywitz, B.A., Pugh, K.R., et al., 1999. Effect of estrogen on brain activation patterns in postmenopausal women during working memory tasks. JAMA 281, 1197–1202.

Sherwin, B.B., 1988. Estrogen and/or androgen replacement therapy and cognitive functioning in surgically menopausal women. Psychoneuroendocrinology 13, 345–357.

Sherwin, B.B., 2003. Estrogen and cognitive functioning in women. Endocrinol. Rev. 24, 133–151.

Sherwin, B.B., Phillips, S., 1990. Estrogen and cognitive functioning in surgically menopausal women. Ann. N. Y. Acad. Sci. 592, 474–475.

Sherwin, B.B., Tulandi, T., 1996. "Add-back" estrogen reverses cognitive deficits induced by a gonadotropin-releasing hormone agonist in women with leiomyomata uteri. J. Clin. Endocrinol. Metab. 81, 2545–2549.

Staresina, B.P., Davachi, L., 2006. Differential encoding mechanisms for subsequent associative recognition and free recall. J. Neurosci. 26, 9162–9172.

Talairach, J., Tournoux, P., 1988. Co-Planar Stereotaxic Atlas of the Human Brain. Georg Thieme, Stuttgart.

Thirion, B., Pinel, P., Meriaux, S., et al., 2007. Analysis of a large fMRI cohort: statistical and methodological issues for group analyses. NeuroImage 35, 105–120.

van Amelsvoort, T., Abel, KM., Robertson, DM., Daly, E., Critchley, H., Whitehead, M., Murphy, DG., 2001. Prolactin response to d-fenfluramine in postmenopausal women on and off ERT: comparison with young women. Psychoneuroendocrinology 26, 493–502.

van Amelsvoort, T., Murphy, D.G.M., Robertson, D., et al., 2003. Effects of long-term estrogen replacement therapy on growth hormone response to pyridostigmine in healthy postmenopausal women. Psychoneuroendocrinology 2003, 101–112.

Wechsler, D., 1999. Wechsler Abbreviated Scale of Intelligence (WASI). Harcourt Assessment, San Antonio, TX.

Young-Hoon, K., Sook-Haeng, J., Woong, C., et al., 2006. Estrogen, cognitive function and negative symptoms in female schizophrenia. Neuropsychobiology 53, 169–175.

Zec, R.F., Trivedi, M.A., 2002. The effects of estrogen replacement therapy on neuropsychological functioning in postmenopausal women with and without dementia: a critical and theoretical review. Neuropsychol. Rev. 12, 65–109.

Update

Hormones and Behavior
Volume 54, Issue 4, September 2008, Page 579

DOI: https://doi.org/10.1016/j.yhbeh.2008.04.009

Hormones and Behavior 54 (2008) 579

Contents lists available at ScienceDirect

Hormones and Behavior

journal homepage: www.elsevier.com/locate/yhbeh

Corrigendum

Corrigendum to "physiological variation in estradiol and brain function: A functional magnetic resonance imaging study of verbal memory across the follicular phase of the menstrual cycle" [Horm. Behav. 53 (2008) 503–508]

Michael C. Craig [a,*], Paul C. Fletcher [b], Eileen M. Daly [a], Janice Rymer [c], Mick Brammer [d], Vincent Giampietro [d], Declan G.M. Murphy [a]

[a] Section of Brain Maturation (PO50), Department of Psychological Medicine, Institute of Psychiatry, Kings College, London SE5 8AF, UK
[b] Brain Mapping Unit (PO189), Department of Psychiatry, University of Cambridge CB2 2QQ, UK
[c] Department of Women's Health, St Thomas' Hospital, London SE1 7EH, UK
[d] Brain Image Analysis Unit (PO89), Centre for Neuroimaging Sciences, Kings College, London SE5 8AF, UK

On page 504, the last sentence under the head *Encoding task* should read: "Women were presented with 100 words, each for a period of 2000 ms, with an inter-stimulus interval of 2000 ms" instead of "Women were presented with 100 words, each for a period of 200 ms, with an inter-stimulus interval of 200 ms."

DOI of original article: 10.1016/j.yhbeh.2007.11.005.
* Corresponding author. Fax: +44 20 7848 0650.
E-mail address: m.craig@iop.kcl.ac.uk (M.C. Craig).

0018-506X/$ – see front matter
doi:10.1016/j.yhbeh.2008.04.009