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Hormones and dichotic listening: Evidence from the study of menstrual cycle effects

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ABSTRACT

This report presents evidence for changes in dichotic listening asymmetries across the menstrual cycle, which replicate studies from our laboratory and others. Increases in the right ear advantage (REA) were present in women at phases of the menstrual cycle associated with higher levels of ovarian hormones. The data also revealed correlations between hormone levels and behavioural measures of asymmetry. For example, the pre-ovulatory surge in luteinising hormone (LH) was related to a decrease in left ear scores, which comprised a key part of the cycle related shift in asymmetry. Further analysis revealed a subgroup of women who had not reached postovulatory status by days 18–25 of the cycle, as verified by low progesterone levels. These women showed laterality profiles at days 18–25 that looked more like the other women when measured at the periovulatory phase (i.e., days 8–11). Data were combined with those from a previous study to highlight the stability of effects. Results showed a distinct menstrual cycle related increase in asymmetry in the combined sample. This final comparison confirmed the nature of sex differences in dichotic listening as being dependent on hormone status in women.

1. Introduction

Dichotic listening is an effective means of examining functional asymmetries in speech perception. The right ear advantage (REA) observed in healthy, right-handed adults has been shown in some studies to be greater in men compared to women (Cowell & Hugdahl, 2000; Wadnerkar, Whiteside, & Cowell, 2008). However, this is a controversial finding which has not always been replicated (Foundas, Corey, Hurley, & Heilman, 2006; Hiscock, Inch, Jacek, Hiscock-Kalil, & Kalil, 1994). Voyer's (1996) meta-analysis showed significant yet small estimated effect sizes for male-greater-than-female asymmetry contrasts derived from verbal dichotic listening tests. Reviews of the dichotic listening literature (Sommer, 2010), as well as large scale studies of healthy men and women (Hugdahl, 2003) have documented that overall, there is considerable overlap between the sexes. There are important underlying reasons why the sex difference has been so elusive – one of the key factors responsible for the effect is the hormonal status of the women sampled. It has been hypothesised that sex differences are evident in analyses that involved females at lower hormone states, such as pre-puberty and postmenopause (Cowell, 2010). Another source of evidence to support the hypothesis comes from the study of women at different phases of the menstrual cycle, specifically comparisons that involve high and low ovarian hormone levels.

Across the life span, both men and women undergo transitions in reproductive status related in part to changes in sex hormone levels. A large literature documents the role of early perinatal hormones in the sexual differentiation process. Changes at puberty are evident in both sexes, and further transitions in later adulthood are particularly salient in the life span development of women who undergo menopause. The dichotic listening literature shows evidence, through examination within and between these key life stages, for a relationship between hormones and the perceptual asymmetry for speech stimuli. For example in a study of twins, right ear advantage on dichotic listening in children was greater in girls from opposite sex dizygotic twin pairs compared to girls from same sex dizygotic twin pairs (Cohen-Bendahan, Buitelaar, van Goozen, & Cohen-Kettenis, 2004). A more recent study has confirmed greater number of right compared to left ear reports in a dichotic listening task delivered to boys (Lust et al., 2010). In contrast, no right-left difference was found in girls. In adults, sex differences were more prominent after age fifty when men showed greater lateralisation than women (Cowell & Hugdahl, 2000). Thus, males showed higher REA on dichotic listening tests when compared to pre-pubertal and postmenopausal females.

Studies of dichotic listening in women of reproductive age show that there is variation in laterality as a function of menstrual cycle phase. Women examined at multiple points within a monthly cycle typically showed a higher REA for verbal stimuli during phases

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when ovarian levels were high (Hampson, 1990a, 1990b; Sanders & Wenmoth, 1998). Changes at the periovulatory and midluteal phases were reflected in increased RE and decreased LE reports. Research from our laboratory examined sex differences in relation to menstrual cycle effects by comparing dichotic listening in a sample of men to women who were studied at the early (low hormone) and later (high hormone) phases of their naturally occurring menstrual cycle. Consistent with prior research, women had lower REA at the menstrual phase and higher REA at the midluteal phase (Wadnerkar et al., 2008). In addition, we showed that sex differences in degree of right ear advantage for perception of speech syllables were modulated by the menstrual cycle. When women at the menstrual phase were compared to men, there was a significant difference with men being more lateralised. When the same women at the midluteal phase were compared to men, there was no difference (Wadnerkar et al., 2008). Together the evidence indicated that sex differences were more likely to be observed when males were compared to females at a low hormone phase in their menstrual cycle (i.e., the menstrual phase). This work suggested further that menstrual cycle phase was one source of variation which may have contributed to controversy in the literature about sex differences in dichotic listening.

Despite progress in the area of hormones and dichotic listening, there remain a number of issues which have not yet been definitively addressed. First, there are still questions pertaining to the stability of menstrual cycle effects which have not always been replicated (Alexander, Altemus, Peterson, & Wexler, 2002). Second, the specific behavioural-endocrine mechanisms underlying effects of the menstrual cycle on dichotic listening have not been fully established. For example, it's not entirely clear whether fluctuations in estrogen, progesterone or both are involved in laterality shifts. When considered together, the issues of cross-study variations and hormone effects raise the possibility that there are individual differences in the degree to which women's dichotic listening asymmetry is affected by the menstrual cycle and by variants to the "typical" 28 day cycle. Therefore, one objective of the current study was to examine variation in speech perception asymmetry in women as a function of three menstrual cycle phases and directly measured levels of the ovarian hormones estrogen and progesterone at each phase. A second objective was to examine the data closely for evidence of individual differences in behavioural-endocrine measures that could be used to delineate subgroups of women. A final objective was to revisit the issue of reproducibility in relation to menstrual cycle effects and sex differences.

2. Methods

Twenty-one healthy women aged 20–30 years (mean age = 25.24 ± 0.74) who reported a history of regularly occurring menstrual cycles were studied as part of a larger research study on hormones, speech and related behaviour. All women selected for the current analysis had complete dichotic listening data for three menstrual cycle phases. Participants were recruited from students and employees of the University of Sheffield and surrounding local community. The study protocol was approved by the Department of Human Communication Sciences Research Ethics Review Panel, University of Sheffield. All participants provided their informed written consent before starting the study; consent was checked and verbally confirmed at the start of each subsequent test session.

Handedness was measured using a behavioural test of forty items designed to deliver scores between −40 (complete left handed) and +40 (complete right handed) (Wadnerkar et al., 2008). IQ was estimated using the 2-test version of the WASI (Wechsler, 1999). All women were right handed (mean score = 29.71 ± 1.23) and had IQ scores at or above average (mean score = 117.43 ± 2.05). All women had English as their only language or as one of multiple fluent languages acquired before the age of six.

Women were screened for past and present injuries, illnesses, and medications that could affect reproductive health, behaviour and brain function. Women were asked to report any current hearing impairment or correction, and any history of hearing related difficulties. Women with past or current hearing problems were excluded from the dichotic listening component of the larger study. All women were free from oral contraceptives, hormonally based contraceptive implants or patches, and other forms of hormonally based medication. In addition, they had not been pregnant or lactating for at least 1 year prior to study participation.

A calendar method was used to estimate the timing of test sessions for the menstrual (days 2–5; low estrogen and progesterone), the periovulatory (days 8–11; high estrogen and low progesterone) and midluteal (days 18–25; high estrogen and progesterone) phases of the menstrual cycle. Due to scheduling difficulties, two women were studied on day 6 for the menstrual phase and one woman was studied on day 28 for the midluteal phase. Mean cycle duration was 29.20 ± 0.96 days (median = 28 days; values based on $n = 20$ ranging from 22 to 41 days) and the midluteal phase was confirmed as falling within 14 days of the onset of the next menstrual cycle in the 16 of the 17 women for whom follow-up data were available (mean backwards count day = 6.94 ± 0.97 based on $n = 17$). Women reported age of menarche as falling between 9 and 15 years (mean age 12.81 ± 0.32).

Progesterone (P), estrogen (estradiol: E); luteinising hormone (LH) and follicular stimulating hormone (FSH) were measured at each test session via venous blood samples. Assays were performed using automated chemiluminescent technology (Bayer Diagnostics, ADVIA Centaur Immunoassay Analyser). Hormone data were available for all women at the midluteal phase, but due to difficulties with the blood draw procedure, one participant was missing data for the menstrual phase and one participant was missing data from the menstrual and periovulatory phase. All available hormone levels were clinically reviewed and deemed within normal limits. Values for the group as a function of cycle phase are presented in Table 1.

The study objectives included investigation of sources of inter-laboratory (i.e., among published studies in the literature) and individual participant differences. Thus, women with cycles longer ($n = 5$) or shorter ($n = 4$) than 28 ± 2 days, or who did not show clear evidence of postovulatory status in the midluteal phase ($n = 5$; 'midluteal' progesterone levels below 10 nmol/L), were included in the study. These women were medically healthy and had estrogen, progesterone, LH and FSH levels that were otherwise within typical limits (their hormone levels did not indicate fertility problems, unexpected early onset of menopause, chronic anovulation or polycystic ovarian syndrome).

A dichotic listening test, with stimulus pairs comprised of syllables /ba/da/ga/pa/ta/ka/, was delivered to women at each cycle phase and scored for number of correct right ear (RE) and left ear (LE) reports (Hugdahl, 2003). Syllables were on average 400 ms in duration with a 4 s gap between each stimulus presentation. Two syllables were delivered simultaneously on each trial, one to each ear. Stimuli were delivered using headphones (Sennheiser eH2270) and a CD player (Sony ZS-D55, set at volume level 3.1). Testing was conducted in a sound treated room. Prior to delivering the test, participants were shown a card printed with the six syllables which were read aloud by the researcher as part of the test instructions (Hugdahl and Asbjørnsen, Dichotic Listening with CV-Syllables Manual). Participants were asked to listen to the syllable presentations through the headphones and verbally report which syllable they heard most clearly on each trial. Thirty dichotic

Table 1
Hormonal characteristics of participants as a function of menstrual cycle phase (mean ± s.e.). (Statistics for cycle days are based on $n = 21$; reduced samples sizes refer to missing data for hormone measures at the menstrual and periovulatory phases.)

Measure	Menstrual phase	Periovulatory phase	Midluteal phase
Cycle days (*n* for hormone data)	3.81 ± 0.28 (20)	9.76 ± 0.23 (19)	22.48 ± 0.60 (21)
Estradiol (pmol/L)	186.15 ± 18.75	450.21 ± 69.81	579.90 ± 57.48
Progesterone (nmol/L)	3.02 ± 0.32	2.65 ± 0.26	30.19 ± 4.64
FSH (IU/L)	5.86 ± 0.40	4.94 ± 0.41	3.21 ± 0.41
LH (IU/L)	4.78 ± 0.38	6.61 ± 0.56	5.77 ± 1.73

and six homonymic trials were administered. Only responses to dichotic trials were used for analysis; homonyms were used to confirm adequate hearing conditions. Correct RE and LE responses served as the primary dependent measures. Some analyses were based on the laterality index computed as: (RE − LE)/(RE + LE).

The cycle phase of the first test session was counterbalanced across women. For the larger study of hormones and speech, 10 women started at the menstrual phase, 7 at the periovulatory phase, and 13 at the midluteal phase. For the 21 participants with complete dichotic listening data sets across the menstrual cycle who were included in this analysis, 8 started in the menstrual phase, 2 in the periovulatory phase, and 11 in the midluteal phase.

3. Results

3.1. Menstrual cycle phase analysis

ANOVA with Ear (Right, Left) and Phase (menstrual, periovulatory, midluteal) as repeated measures was conducted for the number of correct syllable reports. The main effect of Ear was significant ($F = 60.63$, $df = 1, 20$, $p < 0.001$), indicating that there were more RE (mean = 13.05) than LE (mean = 7.94) reports across all cycle phases. Lack of a significant Phase effect confirmed that the averaged number of RE and LE reports remained stable across the menstrual cycle (menstrual mean = 10.69; periovulatory mean = 10.55; midluteal mean = 10.24). Ear × Phase was marginally significant ($F = 2.87$, $df = 2, 40$, $p = 0.069$) which showed that degree of asymmetry varied as a function of Phase. Perceptual asymmetry was lowest at the menstrual phase, increased at the periovulatory phase and again at the midluteal phase with a significant difference in the laterality index between the menstrual and midluteal phases ($t = 2.42$, $df = 20$, $p = 0.025$). This change in asymmetry was the result of LE scores decreasing as RE scores were increasing; LE score changes showed a statistically significant pattern of change with number of LE responses decreasing significantly between the menstrual and midluteal phases ($t = 2.66$, $df = 20$, $p = 0.015$) (see Table 2).

The same ANOVA was conducted with the addition of the between group factor Age. Age group was defined using the median split of age such that women aged 20–24 years ($n = 10$) were compared to women aged 25–30 years ($n = 11$). Results paralleled those above with a similar pattern of effects for Ear ($p < 0.001$), Phase (n.s.) and Phase × Ear ($p = 0.064$). The main effect of Age ($F = 4.29$, $df = 1, 19$, $p = 0.052$) was marginally significant and the Age × Ear interaction ($F = 7.58$, $df = 1, 19$, $p = 0.013$) was significant.

Table 2
Dichotic listening measures for mean right ear (RE) and left ear (LE) correct responses as a function of menstrual cycle phase ($N = 21$). Mean laterality indices (LI) are also presented (LI = (RE − LE)/(RE + LE)).

Cycle phase	LE	RE	LI
Menstrual phase	8.76 ± 0.59	12.62 ± 0.62	0.18 ± 0.05
Periovulatory phase	8.00 ± 0.54	13.10 ± 0.54	0.25 ± 0.04
Midluteal phase	7.05 ± 0.37	13.43 ± 0.57	0.31 ± 0.03

This indicated that there were age differences in overall performance (older women, mean = 10.97, showed a higher number of correct averaged RE and LE reports compared to younger women, mean = 9.97) and laterality (older women were more lateralised, mean laterality index = 0.305, compared to younger women, mean laterality index = 0.181). Age did not interact with Phase or Ear × Phase. Thus, the pattern of asymmetry increasing across the three menstrual cycle phases was present in both the younger and the older group.

A series of ANOVAs was carried out to evaluate any potential effects of experimental order due to the phase when the initial test session was conducted. The overall study of hormones, speech and related behaviour was well counterbalanced for start order, but omission of dichotic listening data for participants who did not have complete dichotic listening data across all three cycle phases led to the following groupings: Women who started in the menstrual phase ($n = 8$); Women who started in the periovulatory phase ($n = 2$) and women who started in the midluteal phase of the cycle ($n = 11$). Therefore, several checks were conducted to evaluate the robustness of the findings above in the context of a range of possible order effects. As above, ANOVA was conducted with Ear (Right, Left) and Phase (menstrual, periovulatory, midluteal) as repeated measures. The analysis was expanded to incorporate the between group variable Order. In one analysis Order referred to menstrual ($n = 8$) or midluteal phase ($n = 11$) start, and the two women starting in the periovulatory phase were omitted. In the second analysis, Order referred to women who started in the low hormone (menstrual phase; $n = 8$) compared to women who started in a higher hormone phases of the cycle (midluteal or periovulatory phase $n = 13$). In the third analysis, Order referred to women who started in the first half of the cycle (menstrual or periovulatory phase; $n = 10$) compared to women who started in the latter half of the cycle (midluteal phase; $n = 11$). For all three analyses, the effects of Ear (*p*-values < 0.001) and Ear × Phase (*p*-values: $p = 0.056$; $p = 0.038$; $p = 0.057$) remained at equivalent levels of significance as the initial ANOVA, and did not interact with Order. These results indicated that overall laterality and laterality changes across the menstrual cycle did not vary as a function of the test Order. The Phase effect remained non-significant and Phase did not interact with Order. The main effect of Order was not significant in two out of the three analyses. Order was marginally significant in the third analysis ($F = 4.29$, $df = 1, 19$, $p = 0.052$) due to a lower average RE and LE score across all phases for women who started in the first half (mean = 9.97) compared to those who started in the latter half of the cycle (mean = 10.97).

3.2. Dichotic listening and hormone correlations: detection of typical and atypical profiles

Correlations were conducted between hormone levels and the RE and LE dichotic listening scores within each cycle phase (Table 3). At the menstrual phase, there was a positive correlation between FSH and RE scores. Higher FSH levels were associated with higher RE scores (results remained significant when day of testing was partialled out). At the periovulatory phase, LH was negatively

Table 3
Correlations between dichotic listening scores [right ear (**RE in bold type**) and left ear correct responses (LE in plain type)] and hormone levels (estradiol, progesterone, LH, FSH) as a function of menstrual cycle phase. One set of hormone values was missing for the menstrual phase and two sets of hormone values were missing for the periovulatory phase. (LH = luteinising hormone; FSH = follicular stimulating hormone; *p*-values for significant correlations are listed in brackets; values have not been adjusted for multiple comparisons).

	Menstrual phase (n = 20)		Periovulatory phase (n = 19)		Midluteal phase (n = 21)	
Ear	LE	**RE**	LE	**RE**	LE	**RE**
Estradiol (pmol/L)	−0.28	**0.17**	0.03	**0.37**	0.14	**0.21**
Progesterone (nmol/L)	0.14	**0.00**	−0.25	**0.16**	0.21	**0.54 [0.012]**
FSH (IU/L)	−0.18	**0.45 [0.048]**	−0.37	**−0.05**	−0.14	**−0.48 [0.027]**
LH (IU/L)	−0.08	**0.05**	−0.55 [0.015]	**0.01**	−0.17	**−0.46 [0.035]**

correlated with LE such that higher LH values were associated with lower LE scores. Several correlations were significant at the midluteal phase. RE scores correlated positively with progesterone and negatively with LH and FSH levels. At this phase in the cycle, women with higher RE scores had hormone profiles consistent with postovulatory status (i.e., progesterone levels had risen while LH and FSH levels had declined).

Examination of the data (Fig. 1) identified five women who, when tested on days estimated to fall within the midluteal phase, showed progesterone levels below 10 nmol/L. This, in conjunction with their overall hormone profiles, indicated that they had not reached postovulatory status. Because their hormone levels were within normal limits for their age, these women were considered to represent a healthy variant of the typical 28 day cycle and were examined separately in relation to their laterality scores. Fig. 2 shows the laterality index scores for the five women with atypical cycle profiles plotted separately from the women with confirmed postovulatory status at the midluteal phase.

3.3. Examination across two dichotic listening studies: sources of variation in women and men

For purposes of establishing the stability of menstrual cycle trends, data from a previous study conducted in our laboratory were combined with those from the current study. Participants were healthy adults (25 women; 20 men), aged 20–25 years, who were recruited from the University of Sheffield Community. Cognitive and health status was comparable to adults in the current study and dichotic listening was conducted using the same stimuli. Men were studied once, and all women were studied at the menstrual and midluteal phases using a within-subjects repeated-measures design. Full details of the study can be found in Wadnerkar et al. (2008) which published data combined across three attention conditions. Data from women (studied at the menstrual and midluteal phases) using only the non-forced condition (Cowell, 2010; Wadnerkar, 2008), as applied in the current study, were plotted together with data from the current sample of women (studied at the menstrual, periovulatory and midluteal phases). A laterality index was computed for all participants and is plotted on the *y*-axis of Fig. 3. For women, day of testing was plotted on the *x*-axis. Women in both studies were tested at the menstrual and midluteal phases which accounts for the greater number of data points in days 2–5 and 18–25 compared to the periovulatory phase (days 8–11). As explained in the methods, some women were tested on days just outside the parameters of the main study design. Data for men are plotted on the far right-hand side of the *x*-axis for comparison.

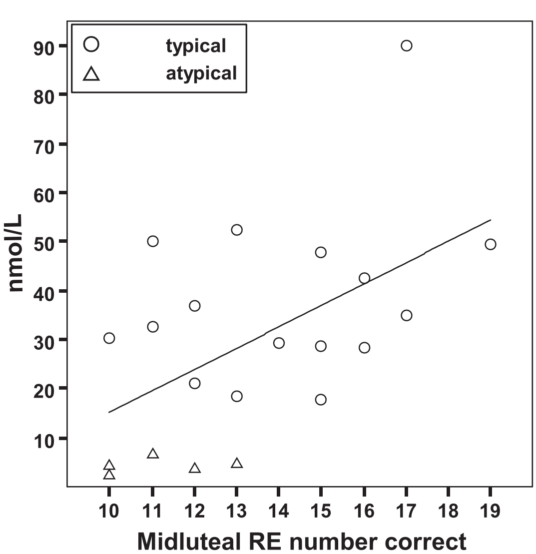

Fig. 1. Number of correct RE responses at the midluteal phase of the menstrual cycle plotted with progesterone levels. Participant groups are delineated as: (circles; "typical") women who had hormone levels consistent with a postovulatory midluteal status; and (triangles; "atypical") women whose hormone levels were incompatible with postovulatory midluteal status. When all women were included in analysis, the correlation between these variables was significant (r = 0.54, n = 21, p < 0.05). The regression line for the whole group is plotted above.

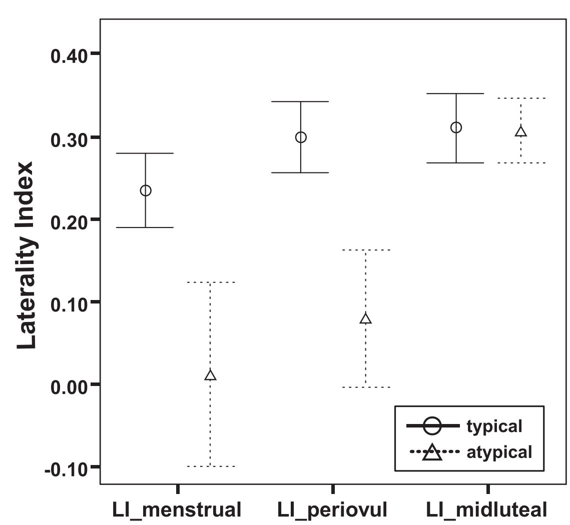

Fig. 2. Laterality index for women at each menstrual cycle phase. Women who showed hormonal profiles consistent with postovulatory status in days 18–25 were classified as typical. Women who showed hormonal profiles inconsistent with postovulatory status in days 18–25 were classified as atypical. Women with atypical cycles appear to show a more radical shift in laterality as a function of menstrual cycle phase compared to women with typical cycles. In addition, the largest increase in typical scores occurred between menstrual and periovulatory (periovul) phases. The largest increase in atypical scores occurred between the periovulatory and midluteal phases. Thus, patterns in the atypical group appear to be "shifted" or "lagged" behind changes seen in the typical group. (Laterality index (LI) = (RE − LE)/(RE + LE); periovulatory (periovul)).

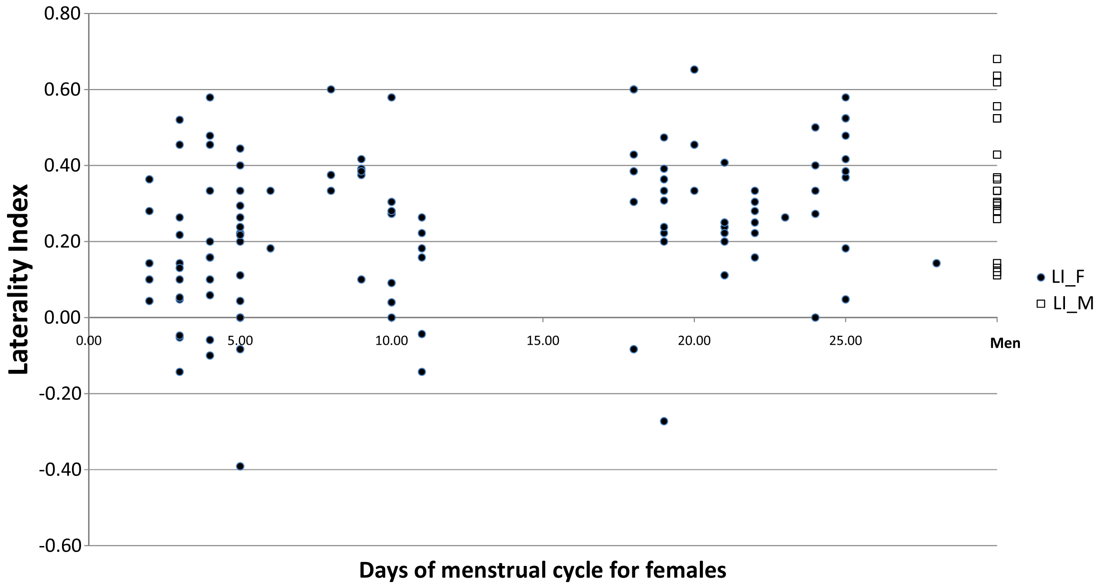

Fig. 3. Laterality index plotted as a function of cycle day for women (filled circles). Data for men are plotted at the far right of the *x*-axis (open squares). Laterality index scores above zero indicate a right ear advantage. Data for this figure were drawn from two studies. Twenty-five women studied at menstrual and midluteal cycle phases and men studied once were from Wadnerkar et al. (2008). Twenty-one women studied at the menstrual, periovulatory and midluteal cycle phases were from the current report. See the text for details of data trends. (Laterality index = (RE − LE)/(RE + LE); LI_F laterality index for females; LI_M laterality index for males).

The imbalance of study designs (two versus three phases) precluded combined statistical analysis for women. However, inspection of the summary statistics and raw data provide insight into the role of within-sex variation in determining the nature of between-sex variation. In women studied between days 2 and 11, the median laterality score (median = 0.20; range = 0.99) was lower than that for women studied between days 18 and 28 of the cycle (median = 0.32; range = 0.92). The median value for women at days 18–28 of the cycle was virtually identical to that observed for men (median = 0.33; range = 0.57). Data for women were distributed symmetrically around the median when examined during the earlier and latter halves of the cycle. In contrast, data points for men were skewed toward the rightward (i.e., positive) end of the laterality index.

4. Discussion

The current study explored the impact of hormones on adult female dichotic listening asymmetries at several levels of analysis. The data showed sources of hormone related variation as a function of within-subjects comparisons and in the examination of individual differences. Together the data shed further light on the nature of hormonally based sex differences in adults, and contribute to the characterisation of sex differences and hormone effects across the life span.

Data from the measurement of dichotic listening across the menstrual cycle showed results consistent with prior research from our laboratory (Wadnerkar et al., 2008). For example, the mean laterality scores for women at the menstrual phase in the current study were (mean = 0.18) equivalent to data from the previous study (mean = 0.16) (Cowell, 2010). Parallel results from the current (mean = 0.31) and previous study (mean = 0.31) were also found at the midluteal phase (Cowell, 2010). This provides evidence for reproducibility with regard to the non-forced dichotic listening task in healthy young women, where time of testing is estimated to correspond to the low or high hormone phase of the menstrual cycle. In the current study, the mean laterality index at the periovulatory phase was midway between those for the menstrual and midluteal phases. Data from individual right and left ear responses indicated changes in both ears, but with more statistically significant effects in LE decreases compared to RE increases across the cycle. The presence of change across the menstrual cycle in reporting from the right and left ears is consistent with recent ERP data in relation to dichotic presentation of words in a semantic categorisation paradigm. Tillman (2010) showed reduced latency in processing stimuli from the left ear to the right hemisphere at the low-estrogen menstrual phase and reduced latency from the right ear to the left hemisphere in the same women tested at the high-estrogen follicular stage.

Cycle related changes provide an indirect indication that lateralised perceptual processing varies as a function of hormone fluctuations. However, there are numerous hormones involved in regulating the menstrual cycle (Ledger, 2010) and it is not clear from the literature which ones are more instrumental in relation to cognitive changes such as those probed by dichotic listening of syllables. Having access to hormone levels should allow the researcher to examine direct relationships between hormones and behaviour. Also, because examination of hormone levels allows one to determine the occurrence of key events such as ovulation, they are important for detecting whether women have all followed similar hormone fluctuations at particular points in the monthly cycle. Looking at relationships within phase, the current study showed several correlations between hormones and behaviour. Progesterone correlated with number of RE reports at the midluteal phase. This relationship provided multilayered insights into the data. First, a subgroup of five women were identified as having progesterone levels lower than expected for the midluteal cycle phase, and lower than all other women measured at this phase. These five women all had RE scores below the mean value of 13.43. Removing these cases from the analysis resulted in a decrease of the correlation from 0.54 to 0.33. Together, the results indicated a correlation formed in part by the inclusion of an atypically cycling subgroup, and that postovulatory status with its associated rise in progesterone is one contributory factor in increasing lateralisation across the menstrual cycle.

Higher RE scores were also associated with increased FSH levels in the menstrual phase and decreased FSH and LH at the midluteal phase. Why there should be links between FSH, LH and neurofunctional asymmetry is not clear, particularly since FSH showed both positive and negative correlations with the same behavioural measure. On the surface this appears to indicate that laterality increased at two points in the cycle which coincided with: (i) the transition from the menstrual to the periovulatory phase (associated with the ovulatory FSH surge); and (ii), the transition from the periovulatory to the midluteal phase (when increases in progesterone drive decreases in both LH and FSH). Future research will be needed to rule out the existence of a possible latent variable or epiphenomenon mediating this system. However, there is an alternative set of explanations that associates functional asymmetry more directly with key hormonal events. For example, it is possible that shifts in perceptual asymmetry are linked with the fertile period of the menstrual cycle. This hypothesis is most clearly supported in the current study through the correlation observed at the periovulatory phase, where higher LH was associated with lower LE scores. LE scores were shown to decrease significantly between the menstrual and midluteal phases and as such appear to be a key factor in the overall cycle related shift in dichotic listening asymmetry. Mean scores (see Table 2) show that this trend begins between the menstrual and periovulatory phases. The shift in laterality appears to be linked with the surge of LH that occurs prior to ovulation and which may be a behavioural indicator of midcycle changes in right hemisphere function. Dichotic listening has been used as a probe to detect attentional differences in shadowing for courtship language at the fertile phase of the menstrual cycle (Rosen & Lopez, 2009). Whether there are any subtle reproductive advantages to being more lateralised at ovulation remains open to debate. However, it seems clear that dichotic listening is a highly sensitive means of tapping into the variations in lateralised perceptual states experienced by healthy women across the menstrual cycle to the extent that it may be developed as a behavioural correlate to fertility status.

The current study provides a basis from which to ask again, "Is there a sex difference in the right ear advantage?" The answer is "yes." However, the data reveal a pattern of sex differences which is not best expressed as a single difference in mean scores from male and female samples. One must consider that the measure is sensitive to changes within-women across the menstrual cycle. The current study replicated previous work from our lab and others showing greater REA in women for verbal stimuli at the phases of the cycle when ovarian hormones are higher (Hampson, 1990a, 1990b; Sanders & Wenmoth, 1998). It also closely examined the role of hormone levels in detecting individual differences. The microscopic analysis identified that some women originally estimated (via the calendar method) to be at the periovulatory and midluteal phases may in fact have been at earlier respective phases corresponding to a longer cycle duration or anovulatory cycle. The data in Fig. 3 show why sex differences, i.e., males having greater REA than females, are so difficult to replicate. If a sample includes more women in the higher hormone phase of the cycle, which is more likely in the latter 2 weeks, then there is minimal chance of detecting a sex difference. Both men and women (right handers, aged 20–30 years) fell mainly within the 0.20–0.60% range. If a sample includes more women in the lower hormone phase of the cycle, which is more likely in the first 2 weeks of the cycle, then there is a greater chance of detecting a sex difference. Women showed more representation at this phase within the 0.00–0.20% laterality index range. Thus, women show a degree of within-subject variation that is related to the menstrual cycle. The sex difference in measures of central tendency is clearly dependent on the cycle phase of the women included in the comparison. Yet, there are additional features of the data which differentiate men and women. Compared to men, samples of women have larger laterality ranges and more symmetrical distributions at both the early and latter phases of the cycle compared to men. The data currently support the hypothesis that individual women function at the same level of perceptual accuracy, but at different lateralised states over the course of 4–5 weeks. This is a difference that would not be expected in men.

Hausmann, Bayer and colleagues have made notable progress in setting and testing hypotheses about the role of ovarian hormones in the modulation of functional laterality and interhemispheric interactions across the menstrual cycle (Hausmann & Bayer, 2010). One set of mechanisms proposed by their work, interhemispheric inhibition and its reduction, may have relevance to the changes observed in dichotic listening. It should be noted that their models are based on a range of behavioural and neurocognitive measures some of which show directional patterns of laterality change in relation to menstrual cycle phase that differ (i.e., stronger asymmetry at low hormone phase) from those observed in the current dichotic listening study (i.e., stronger asymmetry at high hormone phases) (Hausmann, Becker, Gather, & Güntürkün, 2002; Hausmann & Güntürkün, 2000). Thus, comparisons below are intended to draw connections at a fairly general, rather than a task-specific level, about the possible role of hormones in modulating hemispheric function. The literature on interhemispheric connections in relation to dichotic listening indicates a key role for excitatory connections (i.e., callosal size reduction and split brain cases are related to LE extinction and high rightward perceptual asymmetry) (Barkhof et al., 1998; Varley, Cowell, Gibson, & Romanowski, 2005). Thus, fewer LE responses, which are thought to rely in part on cross-callosal connectivity from the right to the left temporal cortex, at high hormonal phases may be due to a decrease in callosal right- to left-hemisphere transfer. However, as conceptualised by Hausmann and Bayer (2010), an alternative framework suggests that laterality shifts at the midluteal phase, which also involve increased RE response, could be due in part to a reduction of interhemispheric inhibition on left temporal lobe processing of RE input in the context of dichotic competition. Thus, it may be the case that subsystems of lateralised mechanisms coexist at various processing levels which do not necessarily respond to hormone fluctuations in a uniform fashion. For example, progesterone-related effects of interhemispheric inhibition (Hausmann & Bayer, 2010) may provide a component of laterality change that operates alongside estrogen-related changes in ear-to-hemisphere latencies (Tillman, 2010). The current study on dichotic listening was conducted as one part of a research programme looking at speech perception and production as a function of ovarian hormones in women of reproductive age. Given the key role of hormones in communicative function in humans and other species (Hauber, Cassey, Woolley, & Theunissen, 2007; Nottebohm et al., 1990), it is possible that auditory-motor speech functions (Bolhuis, Okanoya, & Scharff, 2010) are governed by biological variants of the principles set out by Hausmann and Bayer (2010) and Tillman (2010) in relation to their studies of lexical, semantic and figural processing functions.

The data in this study were drawn from a study designed to examine the impact of hormones on speech functions in healthy adult women. The dichotic listening data represented a subset of the total sample of women as well as a subset of the test battery administered. Thus, while most aspects of the larger study were fully powered, the sample of women for whom there was complete dichotic listening data was reduced. This was acceptable for confirmation-based analysis of menstrual versus midluteal phase effects on laterality (Wadnerkar et al., 2008), but meant that other analyses such as the multiple correlations among dichotic listening and hormone measures should be viewed in an exploratory light. The reduced sample also placed an imbalance in terms of how many women started the study in each menstrual cycle phase. However, detailed analysis of order effects confirmed that starting phase did not impact the significance of the Ear × Phase interaction. Exploration of possible age effects similarly confirmed robustness of the Ear × Phase interaction. This analysis also revealed that even within a tightly constrained age range of 20–30 years, variation in terms of overall performance and laterality was possible. A final limitation of the current study is that hearing sensitivity was not formally measured. The within-subjects repeated-measures design provided the basis for each woman to serve as her own perceptual control. In addition, the stability of averaged RE and LE scores across phases (i.e., lack of main effect of Phase) supports the claim that overall perceptual accuracy was not affected. Yet, these points do not fully address how possible changes in asymmetry of sensory acuity across the menstrual cycle may contribute to the observed changes at the perceptual level.

The current study provides clarification as to why between-sex differences in dichotic listening asymmetry have been so elusive. In doing so, it has raised new questions as to the many sources of variance that contribute to within-sex differences in women. Taken together, the current study and the compilation with data from our previous study, indicate that within-sex variation in women's dichotic listening profiles is shaped by a complex set of factors. These include menstrual cycle day, cycle length, hormone levels, and possibly other more complex variables latent in the sample (e.g., possible age effects, women with varying baseline asymmetries responding to hormone changes in different ways). Given its sensitivity to individual differences, dichotic listening is an ideal instrument for investigating these phenomena in future research. However, the same sensitivity to individual differences requires that future studies be conducted with larger sample sizes to allow for more fully powered multivariate analytic approaches.

In conclusion, women's perceptual speech processing is highly plastic and operates at varying states of functional asymmetry across days of the menstrual cycle. These findings are consistent with work showing menstrual cycle related changes in lateralised neurocognitive systems in the language domain (Fernandez et al., 2003; Konrad et al., 2008). The current results add to the growing evidence which shows that laterality and interhemispheric dynamics are affected by reproductive hormones. Dichotic listening has proven to be a powerful probe in elucidating these biobehavioural principles.

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