

Relationships Between 24-h LH and Testosterone Concentrations and With Other Pituitary Hormones in Healthy Older Men

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ABSTRACT

Objective: To investigate the relationship between LH and T, which characteristics associate with the strength of this relationship, and their interrelationships with GH, TSH, cortisol, and ACTH.

Design: Hormones were measured in serum samples collected every 10 min during 24 h from 20 healthy men, comprising 10 offspring of long-lived families and 10 control subjects, with a mean (SD) age of 65.6 (5.3) years. We performed cross-correlation analyses to assess the relative strength between two timeseries for all possible time shifts.

Results: Mean (95% CI) maximal correlation was 0.21 (0.10–0.31) at lag time 60 min between LH and total T concentrations. Results were comparable for calculated free, bioavailable, or secretion rates of T. Men with strong LH-T cross-correlations had, compared to men with no cross-correlation, lower fat mass (18.5 (14.9–19.7) vs. 22.3 (18.4–29.4) kg), waist circumference (93.6 (5.7) vs. 103.1 (12.0) cm), hsCRP (0.7 (0.4–1.3) vs. 1.8 (0.8–12.3) mg/L), IL-6 (0.8 (0.6–1.0) vs. 1.2 (0.9–3.0) pg/mL), and 24-h mean LH (4.3 (2.0) vs. 6.1 (1.5) U/L), and stronger LH-T feedforward synchrony (1.5 (0.3) vs. 1.9 (0.2)). Furthermore, T was positively cross-correlated with TSH (0.32 (0.21–0.43)), cortisol (0.26 (0.19–0.33)), and ACTH (0.26 (0.19–0.32)).

Conclusions: LH is followed by T with a delay of 60 min in healthy older men. Men with a strong LH-T relationship had more favorable body composition, inflammatory markers, LH levels, and LH-T feedforward synchrony. We observed positive correlations between T and TSH, cortisol, and ACTH.

Keywords: luteinizing hormone, testosterone, pituitary hormones, cross-correlation, ageing, men

INTRODUCTION

Serum levels of several parameters from the hypothalamic-pituitary-gonadal (HPG) axis change with age in men, which has been reviewed by others (1,2). Total testosterone (T) levels decline moderately, but progressively with age, starting around the age of 30-40 years, while levels of sex hormone binding globulin (SHBG) gradually increase with age, resulting in a steeper decline in serum levels of free T (2-5). The decline in T is a multifactorial process. Intervention studies have shown that ageing in healthy men is accompanied by diminished gonadotropin-releasing hormone (GnRH) output, resulting in less luteinizing hormone (LH) drive on the Leydig cell, diminished testicular responsiveness to LH, while T feedback on the hypothalamus-pituitary unit is also decreased (6,7). The decline in T (free T) levels in males together with several sexual symptoms, when not caused by hypothalamus-pituitary disorders, including tumors, infections and trauma, has been named late onset hypogonadism (LOH) (8,9). Androgen deficiency is worsened by comorbidities, including diabetes mellitus, cardiac failure, renal disease and chronic obstructive lung disease, obesity, medication, unhealthy lifestyle, and increased aromatase activity (1,9,10). Aside from age-related T decline, the increase of SHBG levels may mask a low serum free T concentration. Factors influencing SHBG positively are thyroxine, estrogens, and anti-epileptic drugs, while insulin, IGF-1, prolactin, pro-inflammatory cytokines, and adiponectin decrease SHBG levels (11,12). With advancing age mean population LH levels increase, which can be attributed to diminished feedback on the gonadotrophic cells and hypothalamus centers involved in the secretion of GnRH. The diminished feedback is also revealed by amplified LH frequency and low amplitude pulses (13,14). It is worth noting that studies have shown that obesity, comorbidities, and lifestyle factors might be even better predictors for low T levels than age (3,5,15,16). In line, T levels were not lower in older men compared to younger men in a study with exceptionally healthy men nor in a study with men reporting themselves as having good or excellent health (17,18).

Although the underlying cellular mechanisms of the decline in T levels with age are not entirely clear, it is commonly thought that the age-related decline in T is a large contributor to many problems in older men (13). Therefore, T administration became a popular intervention in both hypogonadal and eugonadal men, and in both middle-aged and older men, especially in the USA (19,20). T administration might influence the secretion of hormones from other hypothalamic-pituitary-‘target gland’ axes. For example, one study in healthy older men showed that long-term low-dose T administration resulted in increased nocturnal growth hormone (GH) secretion (28), but not in spontaneous nocturnal cortisol secretion (29). Besides, with age, not only levels of LH and T change, but levels of other pituitary hormones also change concomitantly with age. For example, elevated thyroid-stimulating hormone (TSH) levels and a decline in GH secretion have been observed with ageing (30-32). It could be hypothesized that these hormonal changes are synchronized with each other, potentially because these endocrine systems share the ability to respond to changes in the environment in order to maintain homeostasis. In support of this hypothesis, anterior pituitary cells share the same embryonic origin, and there is evidence for crosstalk between pituitary cells (33-36). Recently, we observed interrelations between hormones from different hypothalamic-pituitary-‘target gland’ axes, specifically between cortisol and TSH, GH and TSH, and between GH and cortisol concentrations, in healthy older men and women (37).

In a previous publication, we compared 24-h LH and T secretion parameters and the LH-T relationship between 10 healthy older male offspring of long-lived families to 10 healthy older male controls from the Leiden Longevity Study (38). We did not find an association between LH-T parameters and familial longevity. In the present study, we investigated the relationship between 24-h serum LH and T concentrations in the total population of 20 healthy older men from the Leiden Longevity Study and which health characteristics associate with the strength of this relationship. Furthermore, we aimed to determine the interrelationships between LH and T with GH, TSH, cortisol, and ACTH over 24 h. To this end, we performed cross-correlation analyses to assess the

relative strength between two 24-h hormone concentration series at intervals of 10 min for all possible time shifts. Follicle-stimulating hormone (FSH) was not included in this study because its pulsatility is less pronounced due to its long half-life and low amplitude (39).

MATERIALS AND METHODS

Study population

Participants were recruited from the Leiden Longevity Study, which is a family-based study consisting of 421 families with at least two long-lived Caucasian siblings (men ≥ 89 years and women ≥ 91 years) without any selection on health or demographics together with their offspring and the offspring's partners (40). In the Switchbox Leiden Study, 24-h blood samples were collected from 38 healthy older individuals between June 2012 and July 2013 (41). This study comprised 20 offspring of long-lived families, including 10 men and 10 women, and 18 partners of the offspring as a control group, including 10 men and 8 women. Exclusion criteria included a fasting plasma glucose above 7 mmol/L, the presence of any significant chronic, renal, hepatic or endocrine disease, or the use of medication known to influence any hormonal axis (41). For the present analysis, we only included the male participants from the Switchbox Leiden Study. Consequently, 20 participants were included in the analyses, comprising 10 male offspring of long-lived families and 10 male controls. None of the participants indicated that they were using any Biotin or vitamin B8 supplements, which otherwise could have interfered with the ACTH assay (42). The Switchbox Leiden Study protocol P11.116 was approved by the Medical Ethical Committee of the Leiden University Medical Centre and performed according to the Helsinki declaration. All participants gave written informed consent for participation.

Clinical protocol

Full details on the 24-h blood sampling procedure have been described previously (43). In short, a catheter was placed in a vein of the forearm of the non-dominant hand and blood was collected every 10 min starting around 09:00 h. The participants received standardized feeding consisting of

600 kcal Nutridrink (Nutricia Advanced Medical Nutrition, Zoetermeer, The Netherlands) at three fixed times during the day (between 09:00 and 10:00 h, 12:00 and 13:00 h, and 18:00 and 19:00 h). Lights were switched off for approximately 9 h (circa between 23:00 and 08:00 h) to allow the participants to sleep. Height and weight were measured in the research centre. BMI was calculated as weight (in kilograms) divided by the square of height (in meters). Body composition was determined by Bioelectrical Impedance Analysis (BIA) at a fixed frequency of 50 kHz (Bodystat® 1500 Ltd, Isle of Man, British Isles). Waist circumference was measured with a measuring tape midway between the uppermost border of the iliac crest and the lower border of the costal margin. The Pittsburgh Sleep Quality Index questionnaire was used to collect data on habitual bedtime and getting up time during the past month (44).

Hormone assays

All laboratory measurements were performed with fully automated equipment and diagnostics from Roche Diagnostics (Almere, The Netherlands) and Siemens Healthcare diagnostics (The Hague, The Netherlands) at the Department of Clinical Chemistry and Laboratory Medicine of the Leiden University Medical Center in The Netherlands. Full details on the procedures of the hormone assays have been described previously (38,41,45,46).

Levels of LH, T, GH, TSH, cortisol, and ACTH were all measured in blood samples collected every 10 min from all 20 participants. For each participant, all samples from one time series were measured with the same lot number in the same batch. LH [Roche, Cat# 11732234-122, RRID:AB_2800498] and testosterone [Roche, Cat# 05200067-190, RRID:AB_2783736] were measured in EDTA plasma samples collected every 10 min using ECLIA (Electrochemiluminescence) on a Roche Modular E170 immunoanalyser. Human growth hormone with a molecular mass of 22000 Da [Siemens, Cat# L2KGRH2, Research Resource Identifier (RRID): AB_2811291] was measured in serum samples using an IMMULITE® 2000 Xpi Immunoassay system (Siemens Healthcare diagnostics). TSH [Roche, Cat#

11731459, RRID:AB_2756377] and cortisol [Roche, Cat# 11875116, RRID:AB_2811288] were measured in serum samples by ECLIA using cobas reagents and a Roche Modular E170 Immunoanalyser. ACTH [Siemens, Cat# L2KAC2, RRID:AB_2783635] was measured in EDTA samples using an IMMULITE® 2000 Xpi Immunoassay system (Siemens Healthcare diagnostics). The coefficients of variation (CV) in our study ranged between 4.5% and 2.8% for LH, between 4.1% and 3.8% for T, between 5.4% and 7.2% for GH, between 1.4% and 4.2% for TSH, between 2.4% and 5.1% for cortisol, and between 3.8% and 7.7% for ACTH. The data was checked for obvious outliers by four reviewers with expert knowledge in endocrinology by visual inspection of a graphical display of individual hormone profiles from all 20 participants (47).

ft4 (Cat# 6437281190) was measured in serum samples with 1 h intervals by ElectroChemoLuminescence ImmunoAssay (ECLIA) using a Modular E170 Immunoanalyzer in one batch. For ft4, the CV range in our study was 2.4–3.5%. IGF-1 (Cat# IS-3900) was measured in six plasma EDTA samples with 4 h intervals for each participant using an iSYS Immunoassay system of ImmunoDiagnostic Systems (IDS GMBH, Frankfurt am Main, Germany) with a CV range of 1.4–1.8%.

Glucose and insulin were measured in a fasting serum sample withdrawn around 08:30 h at the second day of the 24-h blood sampling. Glucose (Cat# 11876899216) was measured using Roche Hitachi Modular P800 and insulin (Cat# L2KIN2) was measured using IMMULITE® 2000 Xpi Immunoassay. Testosterone is mostly bound to sex hormone-binding globulin (SHBG) and albumin. SHBG (Cat# 03052001190) and albumin (Cat# 11970909216) were measured on Roche Modular analyzers in six EDTA plasma samples with 4-h intervals for each participant around 10:00 h, 14:00 h, 18:00 h, 22:00 h, 02:00 h, and 06:00 h. Bioavailable and free testosterone concentrations were calculated as described in the appendix of Takahashi *et al.* (48). Calculations were based on total T concentrations, which were measured every 10 min, and SHBG and albumin concentrations, which were measured every 4 h. Therefore, for the calculation of bioavailable and free T concentrations for

the period from 09:00 to 13:00 h, the SHBG and albumin levels measured at 10:00 h were used. Subsequently, for the time period from 13:00 to 17:00 h, the SHBG and albumin levels measured at 14:00 h were used, and so on. For each participant, 3 μ L of all (144) samples taken during the 24-h blood sampling were pooled. In this mixture, levels of estradiol (Cat# 06656021190) with a CV range between 6.2% and 10.4% and prolactin (Cat# 03203093190) with a CV range between 1.6% and 2.0% were determined using ECLIA and E170 module of Modular Analytics from Roche Diagnostics.

Additional blood measurements

On the study day, total cholesterol, triglycerides, and HDL cholesterol were measured on the Roche Cobas 8000 Modular. Approximately two weeks before the study day, fasting serum was withdrawn to screen for baseline factors. Dehydroepiandrosterone sulfate (DHEAS) (Cat# L2KDS2) was measured using a solid-phase competitive chemiluminescent enzyme immunoassay with an Immulite 2000 XPI system from Siemens Healthcare diagnostics (The Hague, The Netherlands). High-sensitivity C reactive protein (hsCRP) (Cat# 04628918190) was determined by a particle-enhanced turbidimetric assay using Cobas Integra 800 from Roche Diagnostics. Interleukin 6 (Cat# SS600B) and tumor necrosis factor- α (TNF- α) (Cat# SSTA00D) were measured by ELISA from R&D Systems. All measurements were performed at the Department of Clinical Chemistry and Laboratory Medicine of the Leiden University Medical Center in The Netherlands.

Secretion rate

To determine underlying components of LH and testosterone secretion, 24-h serum LH and testosterone concentration profiles were analyzed by validated deconvolution analysis (49-51). By deconvolution analysis, a hormone concentration profile is decomposed into underlying secretory bursts, basal secretion, elimination of previously secreted hormone, and random experimental variability. The algorithm in the software program MATLAB (the Mathworks, Inc., Natick, MA) first detrends the data and normalizes concentrations by converting them to values between 0 and 1.

Second, successive potential pulse-time sets, each containing one fewer burst, were created by a smoothing process. Finally, a maximum-likelihood expectation deconvolution method estimated all secretion and elimination rates simultaneously for each candidate pulse-time set. For LH, fast half-life was fixed to 6.93 min and slow half-life was estimated as unknown variable between 40 and 120 min (52). For testosterone, fast and slow half-lives were fixed to 1.4 and 27 min, respectively (53). Main outcome parameters are the secretion rate per minute and the pulse frequency. LH concentrations are cross-correlated with the secretion rates of T, which is a measure for the feedforward drive of LH on T (54).

Cross-correlation

Cross-correlation assesses the relative strength between two 24-h time series for all possible time shifts, by calculating linear Pearson's correlation coefficients, as explained in more detail elsewhere (55,56). For example, hormone concentrations in time series A are compared pairwise with those of series B measured simultaneously (zero lag) or measured earlier or later (with a time lag). The unit of one lag time is the interval between two sampling points, so a lag time of 1 means that there is a delay of 10 min between two time series. Cross-correlation analyses were performed using the CCF function in the software program R, version 3.6.2 (The R Foundation for Statistical Computing, Vienna, Austria). The range of tested lag times depends on the number of data points in one time series; the range is lag -18 to 18 (360 min in total) for 144 data points. A correlation is considered significant when the absolute value is greater than $2/(\sqrt{n} - |k|)$, where n is the number of data points in one time series and k is the maximal possible lag (57). Thus, for a time series of 144 data points and a maximal lag of 18, the significance level is 0.18.

Cross-correlation analyses were also performed after stratifying the 24-h data for lights-on period, which is the data from time point 09:00 h up to and including 22:50 h, and lights-off period (23:00 to 08:00 h). Data from 08:00 to 09:00 h were excluded from these stratified analyses because the lights

were switched on at 08:00 h and the remaining hour of the data is too short to perform separate analyses on. For these sub analyses, the lag range and the significance level changed accordingly to a lag range of -16 to 16 (320 min) and significance level of 0.24 for the lights-on period, and a lag range of -14 to 14 (280 min) and significance level of 0.31 for the lights-off period.

Cross-approximate entropy

Bivariate cross-approximate entropy (cross-ApEn) is a scale- and model-independent regularity statistic, which quantifies the joint pattern synchrony between two simultaneously measured time series, with lower cross-ApEn values signifying greater synchrony (58). Cross-ApEn of hormones A-B is different from a cross-ApEn of hormones B-A because A is leading in the first case and following in the second. Changes in the cross-ApEn reflect feedback and/or feedforward alterations within an interlinked axis, with the cross-ApEn of LH-T representing feedforward (a)synchrony and cross-ApEn of T-LH indicating feedback (a)synchrony (54). Cross-ApEn was calculated with a window length of $m = 1$ and a margin of $r = 0.2$ (20% of the SD of the individual subject's hormone time series) with standardized data using a Matlab-based algorithm (Mathworks, Inc., Natick, MA). Because cross-ApEn analyses cannot deal with missing data, missing data points were linearly interpolated.

Statistical analysis

Characteristics of the study participants were calculated using descriptive statistics. Normally distributed variables were presented as mean with standard deviation and non-normally distributed variables were presented as median with interquartile ranges. Differences in participant characteristics between subgroups were assessed by Independent-Samples T Tests for variables that were normally distributed and by Mann-Whitney U tests for not normally distributed variables. Categorical variables were compared between subgroups using a Chi-squared test. Repeated measures (RM) ANOVA, which is a model-independent method, was used to test whether levels of

albumin and SHBG were different between six time points. RM ANOVA was performed with Time (10:00 vs 14:00 vs 18:00 vs 22:00 vs 02:00 vs 06:00) as within-subjects factor and albumin and SHBG levels as dependent variables. All statistical analyses were performed using SPSS for Windows, version 23 (SPSS, Chicago, IL, USA). Figure 1 was made using GraphPad Prism version 8 (GraphPad, San Diego, CA, USA) and figures 2, 3, and 4 were made using R, version 3.6.2.

RESULTS

Characteristics of study participants

Characteristics of study participants are presented in Table 1 for all 20 participants. Participants had a mean (SD) age of 65.6 (5.3) years with a range of 52 to 76 years. The observed mean (SD) BMI of 25.8 (3.2) kg/m² and other anthropometric measurements are normal for this age category. Participants were regular nocturnal sleepers in the month prior to the study day with a median (IQR) habitual bedtime of 23:30 (23:00 – 23:45) h and getting up time of 07:45 (07:00 – 08:15) h, which is similar to the time schedule of the study protocol during the 24-h blood sampling. Fasting glucose and insulin levels were for all participants within the reference range of our laboratory. Two men had hsCRP levels above 10.0 mg/L approximately two weeks before the study day, which may indicate the presence of a low-grade infection. SHBG and albumin levels were within our laboratory reference range for all participants. None of the participants were diagnosed with hypogonadism, but one man had slightly low T levels, with a fasting concentration of 7.50 nmol/L at 09:00 h, and another participant had somewhat high LH levels with a 24-h mean of 9.53 U/L. None of the participants were currently smoking and two participants were drinking more than three units of alcohol per day or more than 20 units per week. In addition, we reported these variables separately for offspring of long-lived families and control subjects and compared these in Table 1, which was partly previously performed (38). We did not find any significant difference between groups in age, anthropometrics, usual bedtime, usual getting up time, metabolic markers, inflammatory markers,

hormones, or LH-T related markers. Evidently, only the median (interquartile range) age of the parents differed significantly (offspring: 89.0 (83.4–95.0) vs. controls: 79.5 (74.6–84.3), $P = 0.02$).

Concentration profiles of SHBG and albumin over 24 h

The concentration profiles of SHBG and albumin are plotted over 24 h in Figure 1 for each of the 20 individual participants, together with the mean and standard error per timepoint. To investigate whether levels of SHBG and albumin differed over time, repeated measures ANOVA was performed with Time as within-subjects factor and protein levels as dependent variable. No significant difference in mean SHBG levels over time was observed ($F(3.9,73.5)=1.4$, $P = 0.25$), but mean albumin levels differed significantly between time points ($F(3.8,71.4)=3.1$, $P = 0.02$). Post hoc t-tests indicated that specifically mean albumin levels at 06:00 h were significantly lower than mean albumin levels at 18:00 h ($P = 0.02$).

Concentration profiles and secretion rates of LH and total, free, and bioavailable T from one individual

In Figure 2, the 24-h serum concentration profiles of LH and T as measured in blood samples withdrawn every 10 min from one random participant are plotted. The secretion rates of LH and T, which were calculated by deconvolution analysis, of the same participant are also visualized over 24 h. Furthermore, 24-h concentration profiles of free T and bioavailable T, calculated using total T, SHBG, and albumin levels, from the same participant are plotted.

Relationship between LH and T

For the cross-correlation of LH and total T concentrations, a mean (95% confidence interval (CI)) maximal correlation of 0.21 (0.10 – 0.31) was found at lag time 60 min, with all positive cross-correlations between lag times 50 and 90 min (see Figure 3a). These results indicate that LH

concentrations are followed by T concentrations with a delay of 50 to 90 min. As published previously (38), comparable results were obtained in offspring of long-lived families and controls.

Stratified for lights-on and lights-off periods

When stratifying for lights-on and -off periods, it was found that the mean maximal cross-correlation between LH and T is stronger during the lights-on period (0.30 (0.21 – 0.39)) at lag time 60 min than during the complete 24-h period (data not shown). The significant cross-correlation disappeared during the lights-off period.

LH concentrations with T secretion rates

If the secretion rates of T are used in the cross-correlation analysis instead of T concentrations, similar results are found. The mean maximal correlation coefficient for LH concentrations with T secretion rates was 0.19 (0.10 – 0.28) at lag time 60 min (Figure 3b).

Calculated free T and bioavailable T

When using 24-h free T data (Figure 3c), the maximal positive correlation was found at lag time 80 min, but this mean correlation coefficient (95% CI) between LH and free T concentrations (0.12 (0.01 – 0.23)) was not significant. The cross-correlations between LH and bioavailable T (Figure 3d) were similar to the results using total T concentrations, with a mean (95% CI) maximal correlation coefficient of 0.18 (0.07 – 0.28) at lag time 60 min, which is borderline significant.

Strong vs. no LH and T cross-correlation

Half of the participants had a strong maximal cross-correlation between LH and total T concentrations, with correlation coefficients above 0.20 (range 0.20 – 0.64) at lag time 60 min. The other half of the participants had no significant maximal cross-correlation between LH and T concentrations, with correlation coefficients between -0.16 and 0.05. Therefore, in Table 2,

participant characteristics are stratified for men with a strong cross-correlation and men without a significant cross-correlation between LH and T concentrations, to compare these two groups. Groups did not differ in chronological age or in their family history, indicated by the distribution of offspring of long-lived families and controls and the mean age of the parents. Although BMI and lean body mass did not significantly differ between groups, fat mass (18.5 (14.9 – 19.7) vs. 22.3 (18.4 – 29.4), $P=0.02$) and waist circumference (93.6 (5.7) vs. 103.1 (12.0), $P=0.04$) were significantly lower in men with a strong LH-T correlation compared to men with no LH-T cross-correlation. Groups did not differ significantly in their metabolic markers, nor in other hormones. However, both mean hsCRP (0.7 (0.4 – 1.3) vs. 1.8 (0.8 – 12.3), $P=0.02$) and IL-6 (0.8 (0.6 – 1.0) vs. 1.2 (0.9 – 3.0), $P=0.02$) levels were lower in men with a strong LH-T correlation than in men with no correlation between LH and T concentrations. While 24-h mean total, free, and bioavailable T levels were comparable between groups, 24-h mean LH levels were significantly ($P=0.04$) lower in men with a strong LH-T correlation with a mean (SD) level of 4.3 (2.0) compared to men without a LH-T cross-correlation (6.1 (1.5)). LH-T cross-ApEn differed significantly ($P=0.009$) between groups, with lower cross-ApEn values signifying greater synchrony, which indicates that men with a strong LH-T correlation also had a stronger feedforward synchrony (1.5 (0.3) vs. 1.9 (0.2)) than men with no correlation between LH and T concentrations. T-LH cross-ApEn, which is a measure for feedback asynchrony, was not significantly different between the groups.

Association of LH-T parameters with age

To investigate whether LH-T parameters and their relationship are associated with age, we dichotomized the group in men with an age below the median age and above the median age to create equally sized groups and compare LH-T parameters between these groups. Results of these comparisons can be found in Table 3. No differences were found in 24-h mean total T levels, but older men had significantly higher SHBG levels and consequently lower calculated 24-h mean levels of free and bioavailable T. Furthermore, albeit not significant, older men tended to have higher 24-h

mean levels of LH. No significant differences were found in the strength of the LH-T relationship, described by cross-correlation analyses between LH and total T concentrations.

Cross-correlations of LH and T with GH, TSH, cortisol, and ACTH

Results of the cross-correlations of LH and T concentrations with GH, TSH, cortisol, and ACTH concentrations are presented in Figure 4 with a graphical summary in Figure 5. No significant cross-correlations were found between LH and GH, LH and TSH, LH and cortisol, LH and ACTH, and between T and GH concentrations (Figure 4a-e). Also not when stratified for lights-on and -off periods or for offspring of long-lived families vs. controls.

A strong cross-correlation was observed between T and TSH (Figure 4f), with a mean (95% CI) maximal correlation coefficient in all men of 0.32 (0.21 – 0.43) at lag time 0. All cross-correlations between lag times -180 and 60 min were significantly positive. When stratifying for offspring of long-lived families and controls, strong cross-correlations were observed in both offspring (0.30 (0.14 – 0.46)) and controls (0.34 (0.18 – 0.49)) at lag time 0. Similar results for the maximal cross-correlation between T and TSH concentrations were obtained in men with a strong LH-T cross-correlation (0.33 (0.15 – 0.50)) compared to men with a weak LH-T cross-correlation (0.31 (0.17 – 0.45)). No significant correlations between T and TSH was found when stratifying for lights-on and -off periods.

For T and cortisol (Figure 4g), the maximal cross-correlation coefficient was 0.26 (0.19 – 0.33) at lag time 60, indicating that T concentrations are followed by cortisol concentrations after 60 min. Between lag times -30 and 180 min, all correlations were positive. Results for offspring (0.28 (0.16 – 0.40)) and controls (0.24 (0.16 – 0.33)) were comparable. When stratifying for men with strong vs. weak LH-T cross-correlation, similar results were found (0.24 (0.11 – 0.36) vs. 0.29 (0.21 – 0.37)). No significant correlations between T and cortisol were found when stratifying for lights-on and -off periods.

The mean (95% CI) maximal cross-correlation coefficient between T and ACTH (Figure 4h) was 0.26 (0.19 – 0.32) at lag time 0. All correlations between lag times -60 and 100 min were weak but significantly positive. Comparable results were obtained for offspring (0.28 (0.17 – 0.38)) and controls (0.23 (0.17 – 0.30)) at lag time 0. Men with a strong LH-T cross-correlation had a similar mean maximal T-ACTH cross-correlation (0.27 (0.17 – 0.36)) compared to men with a weak LH-T cross-correlation (0.24 (0.16 – 0.33)). No significant correlations between T and ACTH was found when stratifying for lights-on and -off periods.

DISCUSSION

In this study, we aimed to determine the relationship between LH and T concentrations over 24 h in 20 healthy older men. Besides, we aimed to determine which health characteristics are associated with the strength of this LH-T relationship. Furthermore, we explored the interrelationships between serum concentrations of LH and T with GH, TSH, cortisol, and ACTH concentrations using 24-h time series data with intervals of 10 min.

We observed a significant positive correlation between LH concentrations and total T concentrations with a lag time of 60 min, which was strongest during daytime. Comparable results were obtained when using calculated free, bioavailable, or secretion rates of T. This indicates that LH concentrations are followed by (free/bioavailable) T concentrations/secretion with a delay of 60 min which agrees with other studies investigating this relationship in healthy young and older men (59-61). Although the magnitude of the correlation between LH-T that we observed here is in line with that found in other studies (59-61), a correlation coefficient of circa 0.20 is relatively weak compared to that found for other hormones within an interlinked hormonal axis, notably ACTH and cortisol. In a bigger, but partly overlapping, population as the present study, a maximal mean (95% CI) correlation coefficient of 0.78 (0.74 – 0.81) was found between 24-h serum ACTH and cortisol

concentrations (37). We hypothesized that calculated free or bioavailable T concentrations might give stronger cross-correlation results than using total T concentrations, but results were similar.

With ageing, LH levels rise while T levels decline, although this decline in T levels could also be caused by health status, including body composition, inflammation, and comorbidities (1,3). Therefore, although this is a healthy population, we wanted to investigate which health factors, including body composition, metabolic and inflammatory markers, and LH-T related markers are associated with the strength of a LH-T relationship in older men. We found that men with a strong LH-T relationship had more favorable body composition, inflammatory markers, LH levels, and LH-T feedforward synchrony, which is a novel finding. It is known that higher BMI and waist circumference are associated with higher levels of chronic inflammation and low T levels (62,63), but an unfavorable body composition, including higher fat mass and waist circumference, has not yet been found to be associated with a weaker LH-T cross-correlation. In line, inflammatory markers also differed between men with a strong vs. no significant LH-T cross-correlation, with lower hsCRP and IL-6 levels in men with a strong relationship between LH and T concentrations. Inflammation is strongly related to the HPG axis, with an inverse relationship between T levels and hsCRP and IL-6 levels (64,65). The importance of the anti-inflammatory action of T is also recently seen in male COVID-19 patients, among which men expressing a genetic polymorphism in the androgen receptor resulting in them being unable to increase their serum T levels had a more severe clinical outcome and the need for intensive care (66). Furthermore, healthy male subjects who received an injection with a dose of 3 or 6 million U of IL-2 had a reduction in feedforward drive of LH on T secretion, which led to a decrease in T secretory-burst frequency (67). This finding is in line with our observation that men with no LH-T correlation had reduced feedforward synchrony compared to men with a strong LH-T relationship, which was expected since the cross-correlation of LH concentrations with T secretion rates is another measure for the feedforward drive of LH on T (54). Men with no LH-T relationship did not have significantly lower 24-h mean total T levels, but 24-mean

LH levels were significantly higher, although still within the reference range. This observation suggests that LH concentrations play a bigger role in determining the strength of LH-T cross-correlations than T concentrations. Thereby, it could indicate a possible more significant LH-receptor resistance and/or diminished testicular responsiveness in men with no LH-T relationship. Chronological age did not significantly differ between groups of strong vs. no LH-T relationship, which could be due to the limited age range of 52 to 76 years. However, all the significant differences found between men with a strong vs. no LH-T correlation are pointing towards the hypothesis that men with no LH-T correlation are being biologically older than men with a strong LH-T relationship. Furthermore, when comparing LH-T parameters between men with an age below and above the median age, we found that older men had significantly higher SHBG levels, lower calculated 24-h mean levels of free and bioavailable T, and tended to have higher 24-h mean levels of LH. Although participants in this study had T levels within the normal range, these results are according to literature, since higher age is a risk factor for developing primary hypogonadism, which is characterized by low free T and high LH levels.

In our exploratory analysis of cross-correlations with other pituitary hormones, we observed positive correlations between T and TSH concentrations with no delay. Since the cross-correlation plots of T and TSH did not show a sharp peak at lag time 0, but positive correlations at a broad window of lag times, this could indicate that both T and TSH are driven by a common regulator instead of one hormone driving the other hormone. Animals that breed seasonally have elevated levels of both T and TSH during winter seasons. TSH and/or thyroid hormones might stimulate the secretion of GnRH and gonadotropin leading to gonadal growth, which is important for reproduction (68,69). Humans are however not seasonal breeders, so these mechanisms could be of greater importance in animals than in humans. The positive correlation between T and TSH concentrations is in contrast to other human studies, which found higher total T levels in subjects with lower TSH levels and lower T levels in men with subclinical or primary hypothyroidism (70,71). Furthermore, we observed positive

correlations between T and ACTH concentrations with no delay, while the positive cross-correlation between T and cortisol concentrations was maximal at lag time 60 min, indicating that T is followed by cortisol after 60 min. It was found that hypercortisolism such as Cushing's syndrome or chronic long-term glucocorticoid therapy, could result in (secondary hypogonadotropic) hypogonadism (72). This is however in the case of severe cortisol excess, while our study is performed in healthy older men with normal hormonal levels. In the cross-correlation plots, not one sharp peak is shown, but a low peak at a broad window of lag times, which could indicate that these hormones are driven by a common regulator instead of one hormone driving the other hormone. Both the HPG axis and the hypothalamic-pituitary-adrenal (HPA) axis are highly influenced by inflammation, which could be such a common regulator. For example, healthy male subjects who received a low-dose IL-2 administration had an increase in cortisol secretion (73). However, in contrast to the HPA axis, the HPG axis responds to inflammation by decreasing its levels (67).

Lastly, we established the 24-h concentration profiles of SHBG and albumin and observed a low amplitude circadian rhythm in albumin levels with higher levels during the day compared to nighttime. Albumin has a half-life of circa three weeks and is not dependent on nutritional status, so this cannot explain the moderate circadian rhythm in albumin levels (74,75).

Limitations of this study were that, although measurements are extensive, the sample size is relatively small with a limited age range, so we do not have data on the oldest old. Furthermore, LC-MS/MS is generally recommended for measuring sex steroids. However, this is only required when levels are below the detection limit, which was not the case for the participants in the current study.

Summarizing, LH concentrations were followed by T concentrations/secretion with a delay of 60 min in healthy older men. The strength of a LH-T relationship was mainly associated with health factors, including body composition and inflammation markers, LH levels and its feedforward drive, while

chronological age and T levels were not associated with the strength of the LH-T relationship. Future research should aim to determine the role of the hypothalamus in this LH-T relationship and determine the importance of a strong LH-T relationship in ageing men. Furthermore, we found that T concentrations were positively correlated with TSH, ACTH, and cortisol concentrations. These exploratory analyses could indicate that T and other hormones are driven by a common regulator or that there is crosstalk between these hormones. More research is needed to determine the biological meaning and clinical consequences of these interrelationships between T and other hormones.

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DATA AVAILABILITY

The datasets analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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LEGENDS FOR FIGURES AND TABLES

Figure 1. Concentration profiles of SHBG and albumin over 24 h

Serum concentrations of SHBG in nmol/L and albumin in g/L were measured in blood which was sampled during 24 h with 4-h intervals for each participant. The individual concentrations profiles are plotted as grey lines. The black line represents the mean per timepoint together with the standard error bars. The asterisk indicates that mean albumin levels at 18:00 h are significantly higher than levels at 06:00 h ($P = 0.02$).

Figure 2. 24-h concentration profiles and secretion rates of LH and (free and bioavailable) T from one individual

The concentration profiles of luteinizing hormone (LH) and testosterone (T), together with the calculated secretion rates, and the calculated concentration profiles of free T and bioavailable T from one representative participant are plotted over 24 h. LH and T concentrations were measured in serum which was sampled every 10 min during 24 h. Secretion rates were calculated using deconvolution analysis and free T and bioavailable T concentrations were calculated using total T, SHBG, and albumin levels.

Figure 3. Cross-correlations between LH and T

Cross-correlations between LH concentrations and a) total T concentrations, b) T secretion rates, c) free T concentrations, and d) bioavailable T concentrations in all 20 participants. Cross-correlation assesses the relative strength between two hormone time series for all possible time shifts. The graph displays the correlation (y-axis) at a lag time in minutes (x-axis) with each grey line corresponding with one participant. The black line indicates the mean correlation for all participants and the two dark grey lines indicate the 95% confidence interval. The significance level is indicated by two straight dotted lines at correlations -0.18 and +0.18. Negative lag times represent a

correlation in which hormone 2 is followed by hormone 1 and positive lag times represent a correlation in which hormone 1 is followed by hormone 2.

Figure 4. Cross-correlations between LH and T concentrations with GH, TSH, cortisol, and ACTH concentrations

Results of the cross-correlation analyses between LH concentrations and a) GH, b) TSH, c) cortisol, and d) ACTH concentrations are plotted, together with the cross-correlations between total T concentrations and e) GH, f) TSH, g) cortisol, and h) ACTH concentrations. Cross-correlation assesses the relative strength between two hormone time series for all possible time shifts. The graph displays the correlation (y-axis) at a lag time in minutes (x-axis) with each grey line corresponding with one participant. The black line indicates the mean correlation for all participants and the two dark grey lines indicate the 95% confidence interval. The significance level is indicated by two straight dotted lines at correlations -0.18 and +0.18. Negative lag times represent a correlation in which hormone 2 is followed by hormone 1 and positive lag times represent a correlation in which hormone 1 is followed by hormone 2.

Figure 5. Summary of cross correlations between LH and T concentrations with GH, TSH, cortisol, and ACTH concentrations

A graphical summary of cross-correlation analyses in all 20 participants. Solid lines represent positive correlations between hormones which is strongest at lag time 0, so without a delay. Solid arrows represent positive correlations between hormones which is strongest at a certain lag time, with the arrow directed towards the hormone which is following the leading hormone. The weight of the line/arrow represents the strength of the correlation.

Table 1. Characteristics of study participants, for all subjects and stratified for offspring of long-lived families and controls

Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one control subject.

Table 2. Characteristics of men with a strong cross-correlation and of men with no cross-correlation between LH and T concentrations

Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one participant. ^cGroups were compared using a Chi-squared test.

Table 3. LH-T characteristics of men aged below and above median age

Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one participant. ^cGroups were compared using a Chi-squared test.

Table 1. Characteristics of study participants, for all subjects and stratified for offspring of long-lived families and controls

| Category | Characteristics | All (N = 20) | Offspring of long-lived families (N = 10) | Controls (N = 10) | P value |
|----------------------|---|-----------------------|---|-----------------------|---------|
| Age | Age (years) | 65.6 (5.3) | 66.6 (6.4) | 64.6 (4.0) | 0.41 |
| Family history | Mean age of parents (years) ^a | 84.5 (75.6 – 89.8) | 89.0 (83.4 – 95.0) | 79.5 (74.6 – 84.3) | 0.02 |
| Anthropometrics | BMI (kg/m ²) ^b | 25.8 (3.2) | 26.0 (3.4) | 25.7 (3.2) | 0.84 |
| | Height (cm) ^{a,b} | 178 (175 – 182) | 177 (175 – 182) | 181 (175 – 184) | 0.60 |
| | Fat mass (kg) ^{a,b} | 19.1 (18.0 – 24.1) | 19.8 (16.4 – 25.2) | 18.5 (18.1 – 23.6) | 0.84 |
| | Lean body mass (kg) ^b | 61.7 (4.9) | 61.5 (5.4) | 61.9 (4.7) | 0.89 |
| | Waist circumference (cm) ^b | 99 (11) | 99 (12) | 98 (9) | 0.96 |
| Sleep | Usual bedtime (h) ^a | 23:30 (23:00 – 23:45) | 23:30 (23:11 – 00:00) | 23:30 (22:53 – 23:30) | 0.28 |
| | Usual getting up time (h) ^a | 07:45 (07:00 – 08:15) | 08:00 (07:30 – 08:30) | 07:15 (06:53 – 08:04) | 0.06 |
| Metabolic markers | Fasting glucose [mmol/L] | 4.9 (0.7) | 5.0 (0.8) | 4.8 (0.4) | 0.48 |
| | Fasting insulin [mU/L] ^a | 6.2 (3.4 – 10.1) | 8.0 (7.5 – 8.5) | 7.3 (6.9 – 8.1) | 0.80 |
| | Total cholesterol [mmol/L] | 5.8 (0.9) | 5.7 (0.9) | 5.8 (1.0) | 0.74 |
| | Triglycerides [mmol/L] ^a | 1.2 (0.9 – 1.3) | 1.0 (0.8 – 1.3) | 1.2 (0.8 – 1.4) | 0.74 |
| | HDL cholesterol [mmol/L] | 1.5 (0.3) | 1.6 (0.4) | 1.4 (0.3) | 0.36 |
| | Cholesterol / HDL ratio | 4 (1.2) | 3.8 (1.2) | 4.2 (1.2) | 0.45 |
| Inflammatory markers | hsCRP [mg/L] ^a | 0.9 (0.7 – 2.5) | 0.7 (0.6 – 3.0) | 1.0 (0.7 – 7.6) | 0.58 |
| | IL-6 [pg/mL] ^a | 1.0 (0.8 – 1.3) | 0.8 (0.6 – 1.3) | 1.1 (0.9 – 1.6) | 0.22 |
| | TNF-α [pg/mL] ^a | 1.5 (1.3 – 2.5) | 1.7 (1.4 – 4.0) | 1.4 (1.3 – 2.2) | 0.22 |
| Hormones | DHEAS [umol/L] ^a | 3.3 (1.7 – 5.9) | 4.0 (1.5 – 5.9) | 2.6 (2.0 – 6.4) | 0.74 |
| | Estradiol (24-h pool) [pmol/L] | 81.0 (20.3) | 80.8 (23.2) | 81.1 (18.1) | 0.98 |
| | Prolactin (24-h pool) [μg/L] ^a | 8.9 (7.5 – 9.4) | 8.9 (7.8 – 9.5) | 8.4 (7.4 – 9.7) | 0.63 |
| | IGF-1 (24-mean) [nmol/L] | 16.0 (2.9) | 15.5 (3.0) | 16.4 (2.9) | 0.47 |
| | fT4 (24-h mean) [pmol/L] | 13.8 (1.9) | 13.4 (1.6) | 14.3 (2.1) | 0.33 |

| | | | | | |
|----------------------|--|--------------------|--------------------|--------------------|------|
| LH-T-related markers | SHBG (24-h mean) [nmol/L] | 21.2 (6.9) | 21.3 (7.9) | 21.1 (6.3) | 0.95 |
| | albumin (24-h mean) [g/L] | 36.9 (1.8) | 36.7 (1.8) | 37.1 (1.8) | 0.58 |
| | LH (24-h mean) [U/L] | 5.2 (2.0) | 5.3 (2.0) | 5.1 (2.1) | 0.82 |
| | T (24-h mean) [nmol/L] | 14.4 (3.6) | 14.8 (3.5) | 14.0 (3.8) | 0.63 |
| | Calculated free T (24-h mean) [ng/dL] ^a | 12.0 (11.2 – 9.4) | 13.7 (11.3 – 17.9) | 11.6 (11.0 – 14.6) | 0.32 |
| | Calculated bioavailable T (24-h mean) [ng/dL] ^a | 122 (116 – 175) | 144 (115 – 195) | 119 (117 – 159) | 0.85 |
| | LH pulse frequency | 12.8 (2.1) | 13.2 (1.9) | 12.3 (2.3) | 0.35 |
| | T pulse frequency ^a | 21.0 (16.0 – 25.0) | 22.0 (14.8 – 25.3) | 20.5 (16.0 – 25.3) | 0.99 |
| | LH-T cross-ApEn (feedforward asynchrony) | 1.7 (0.3) | 1.8 (0.2) | 1.6 (0.3) | 0.27 |
| | T-LH cross-ApEn (feedback asynchrony) | 1.9 (0.3) | 2.0 (0.2) | 1.8 (0.4) | 0.17 |

Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one control subject.

Table 2. Characteristics of men with a strong cross-correlation and of men with no cross-correlation between LH and T concentrations

| Category | Characteristics | Strong LH-T correlation (N = 10) | No LH-T correlation (N = 10) | P value |
|----------------------|---|----------------------------------|------------------------------|-------------------|
| Age | Age (years) | 64.6 (6.9) | 66.6 (3.0) | 0.39 |
| Family history | Offspring of long-lived family, N (%) | 4 (40) | 6 (60) | 0.37 ^c |
| | Mean age of parents (years) ^a | 82.8 (75.5 – 86.8) | 85.3 (76.3 – 92.4) | 0.53 |
| Anthropometrics | BMI (kg/m ²) ^b | 24.6 (1.7) | 27.0 (3.9) | 0.11 |
| | Height (cm) ^{a,b} | 176 (175 – 184) | 180 (176 – 182) | 0.66 |
| | Fat mass (kg) ^{a,b} | 18.5 (14.9 – 19.7) | 22.3 (18.4 – 29.4) | 0.02 |
| | Lean body mass (kg) ^b | 61.5 (3.8) | 61.8 (6.0) | 0.91 |
| | Waist circumference (cm) ^b | 93.6 (5.7) | 103.1 (12.0) | 0.04 |
| Sleep | Usual bedtime (h) ^a | 23:30 (23:00 – 23:45) | 23:15 (23:00 – 23:30) | 0.58 |
| | Usual getting up time (h) ^a | 07:15 (06:45 – 08:15) | 08:00 (07:30 – 08:15) | 0.32 |
| Metabolic markers | Fasting glucose [mmol/L] | 5.1 (0.6) | 4.7 (0.7) | 0.28 |
| | Fasting insulin [mU/L] ^a | 4.2 (2.8 – 7.5) | 8.1 (3.7 – 11.1) | 0.12 |
| | Total cholesterol [mmol/L] | 5.4 (0.9) | 6.1 (0.9) | 0.12 |
| | Triglycerides [mmol/L] ^a | 1.1 (0.8 – 1.4) | 1.2 (0.8 – 1.3) | 0.74 |
| | HDL cholesterol [mmol/L] | 1.5 (0.3) | 1.5 (0.4) | 0.98 |
| | Cholesterol / HDL ratio | 3.8 (1.2) | 4.2 (1.2) | 0.45 |
| Inflammatory markers | hsCRP [mg/L] ^a | 0.7 (0.4 – 1.3) | 1.8 (0.8 – 12.3) | 0.02 |
| | IL-6 [pg/mL] ^a | 0.8 (0.6 – 1.0) | 1.2 (0.9 – 3.0) | 0.02 |
| | TNF-α [pg/mL] ^a | 1.5 (1.3 – 2.2) | 1.8 (1.3 – 3.3) | 0.48 |
| Hormones | DHEAS [umol/L] ^a | 2.6 (1.9 – 5.9) | 3.6 (1.5 – 6.0) | 0.99 |
| | Estradiol (24-h pool) [pmol/L] | 75.4 (19.1) | 86.5 (20.8) | 0.23 |
| | Prolactin (24-h pool) [μg/L] ^a | 9.2 (7.5 – 10.2) | 8.6 (7.5 – 9.2) | 0.58 |
| | IGF-1 (24-h mean) [nmol/L] | 16.7 (3.6) | 15.3 (2.0) | 0.29 |
| | ftT4 (24-h mean) [pmol/L] | 13.6 (1.9) | 14.1 (1.9) | 0.61 |

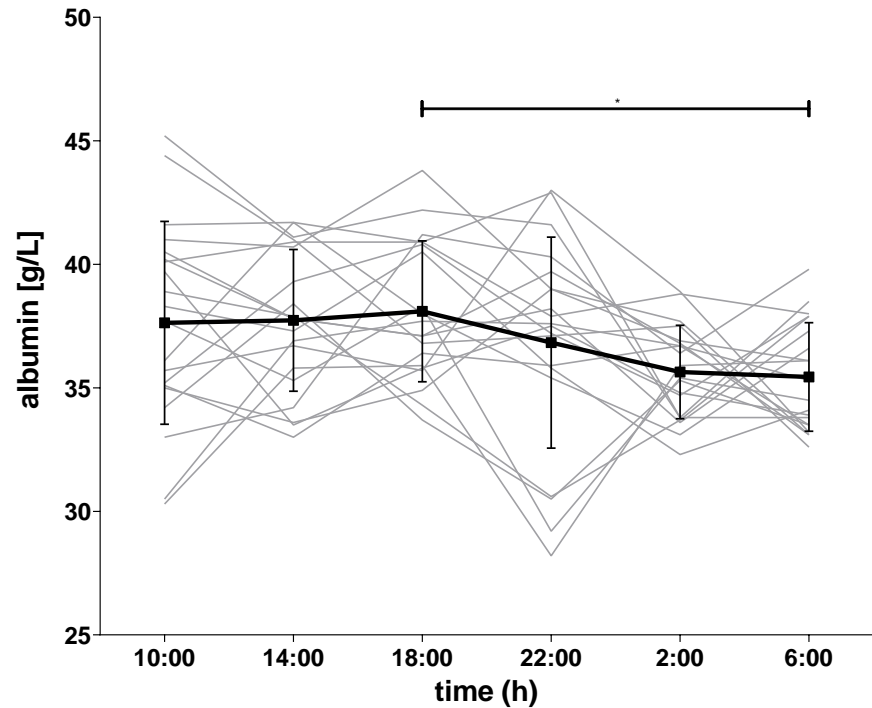
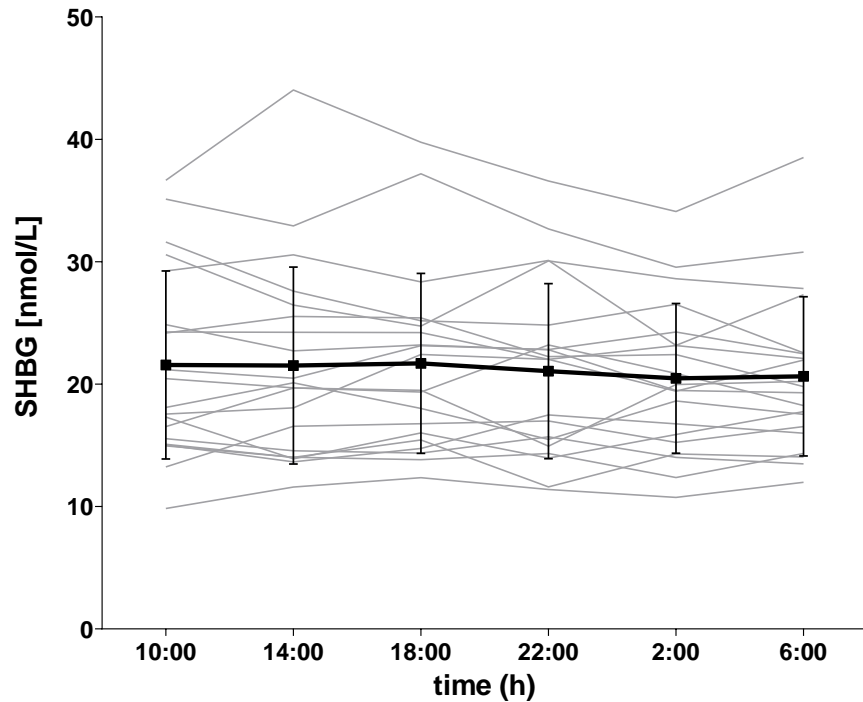
| | | | | |
|----------------------|--|--------------------|---------------------|------------------|
| LH-T-related markers | SHBG (24-h mean) [nmol/L] | 22.4 (7.8) | 19.9 (6.1) | 0.45 |
| | albumin (24-h mean) [g/L] | 37.3 (1.5) | 36.5 (2.0) | 0.30 |
| | LH (24-h mean) [U/L] | 4.3 (2.0) | 6.1 (1.5) | 0.04 |
| | T (24-h mean) [nmol/L] | 14.6 (2.7) | 14.2 (4.4) | 0.80 |
| | Calculated free T (24-h mean) [ng/dL] ^a | 12.3 (11.0 – 16.0) | 12.0 (11.3 – 18.4) | 0.58 |
| | Calculated bioavailable T (24-h mean) [ng/dL] ^a | 129 (117 – 171) | 120 (115 – 198) | 0.68 |
| | LH pulse frequency | 12.1 (2.3) | 13.4 (1.6) | 0.17 |
| | T pulse frequency ^a | 24.5 (18.3 – 26.0) | 18.5 (14.8 – 23.5) | 0.09 |
| | LH-T cross-correlation | 0.36 (0.30 – 0.56) | 0.01 (-0.02 – 0.06) | <0.001 |
| | LH-T cross-ApEn (feedforward asynchrony) | 1.5 (0.3) | 1.9 (0.2) | 0.009 |
| | T-LH cross-ApEn (feedback asynchrony) | 1.8 (0.3) | 2.0 (0.3) | 0.18 |

Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one participant. ^cGroups were compared using a Chi-squared test.

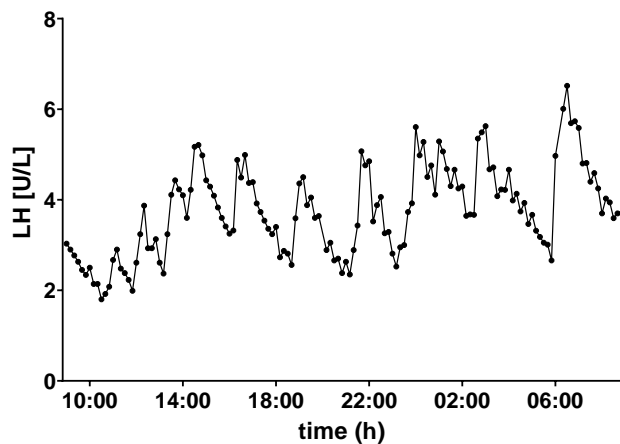
Table 3. LH-T characteristics of men aged below and above median age

| Characteristics | Age below median (N = 10) | Age above median (N = 10) | P value |
|--|------------------------------|------------------------------|------------------|
| Age (years) | 61.9 (4.5) | 69.3 (3.0) | <0.001 |
| SHBG (24-h mean) [nmol/L] | 17.9 (5.3) | 24.4 (7.1) | 0.03 |
| albumin (24-h mean) [g/L] | 37.5 (1.6) | 36.3 (1.8) | 0.15 |
| LH (24-h mean) [U/L] | 4.4 (1.6) | 6.0 (2.1) | 0.08 |
| T (24-h mean) [nmol/L] | 14.4 (3.9) | 14.5 (3.5) | 0.93 |
| Calculated free T (24-h mean) [ng/dL] ^a | 15.5 (12.5 – 18.2) | 11.3 (11.0 – 11.9) | 0.02 |
| Calculated bioavailable T (24-h mean) [ng/dL] ^a | 167 (132 – 199) | 117 (115 – 121) | 0.02 |
| LH pulse frequency | 12.8 (2.0) | 12.7 (2.3) | 0.92 |
| T pulse frequency ^a | 22.5 (17.3 – 25.0) | 19.5 (15.5 – 26.3) | 0.91 |
| LH-T cross-correlation ^a | 0.15 (0.01 – 0.54) | 0.16 (-0.02 – 0.35) | 0.58 |
| LH-T cross-ApEn (feedforward asynchrony) | 1.7 (0.3) | 1.7 (0.2) | 0.65 |
| T-LH cross-ApEn (feedback asynchrony) | 1.9 (0.3) | 2.0 (0.3) | 0.64 |

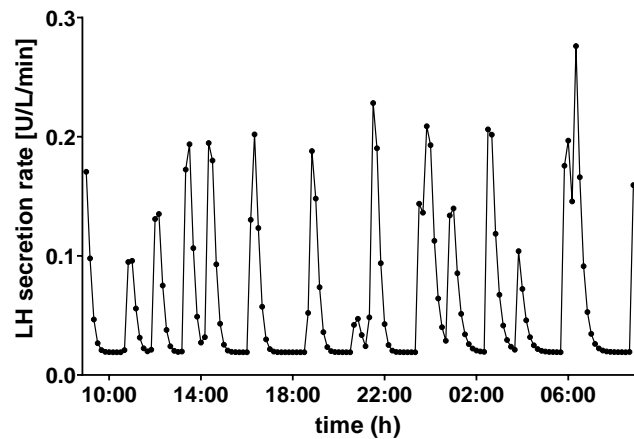
Unless indicated otherwise, data are presented as mean with standard deviation and groups were compared using Independent-Samples T Tests. ^aData are presented as median with interquartile range and groups were compared using Mann-Whitney U tests. ^bData were not available for one participant. ^cGroups were compared using a Chi-squared test.



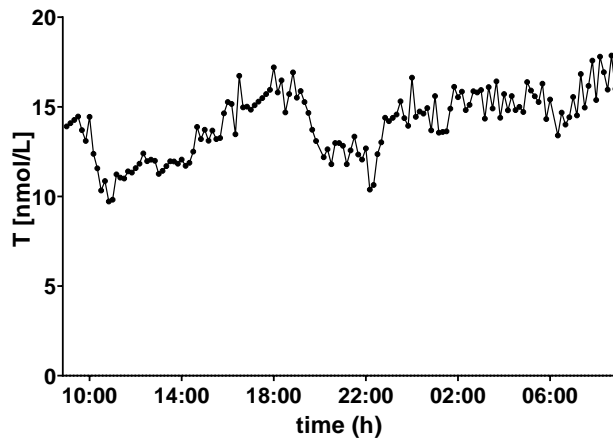
LH concentration



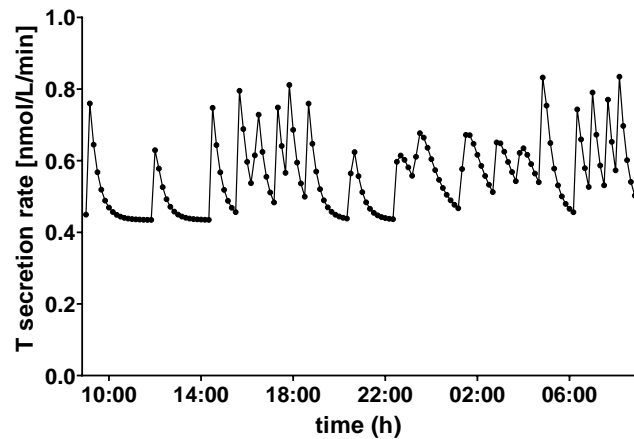
LH secretion rate



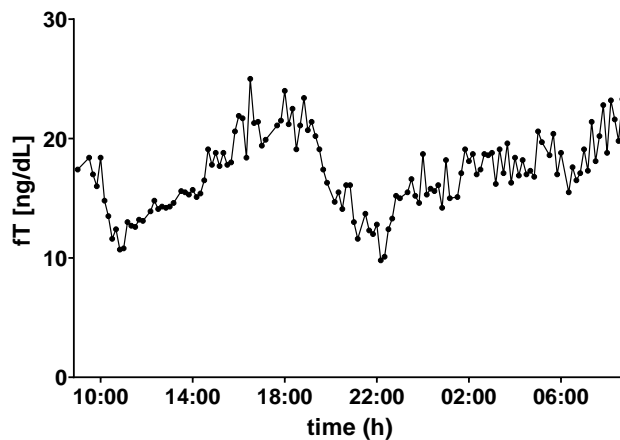
T concentration



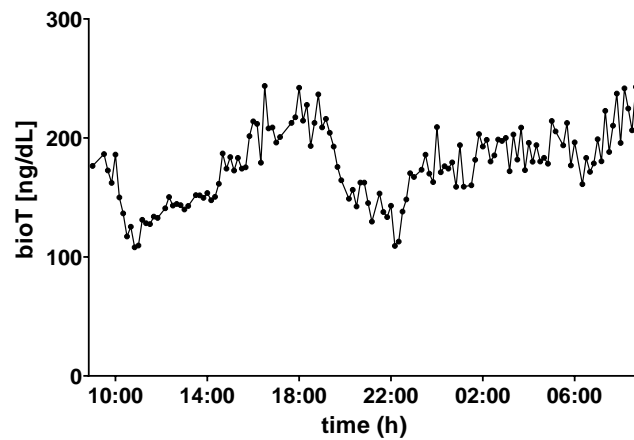
T secretion rate



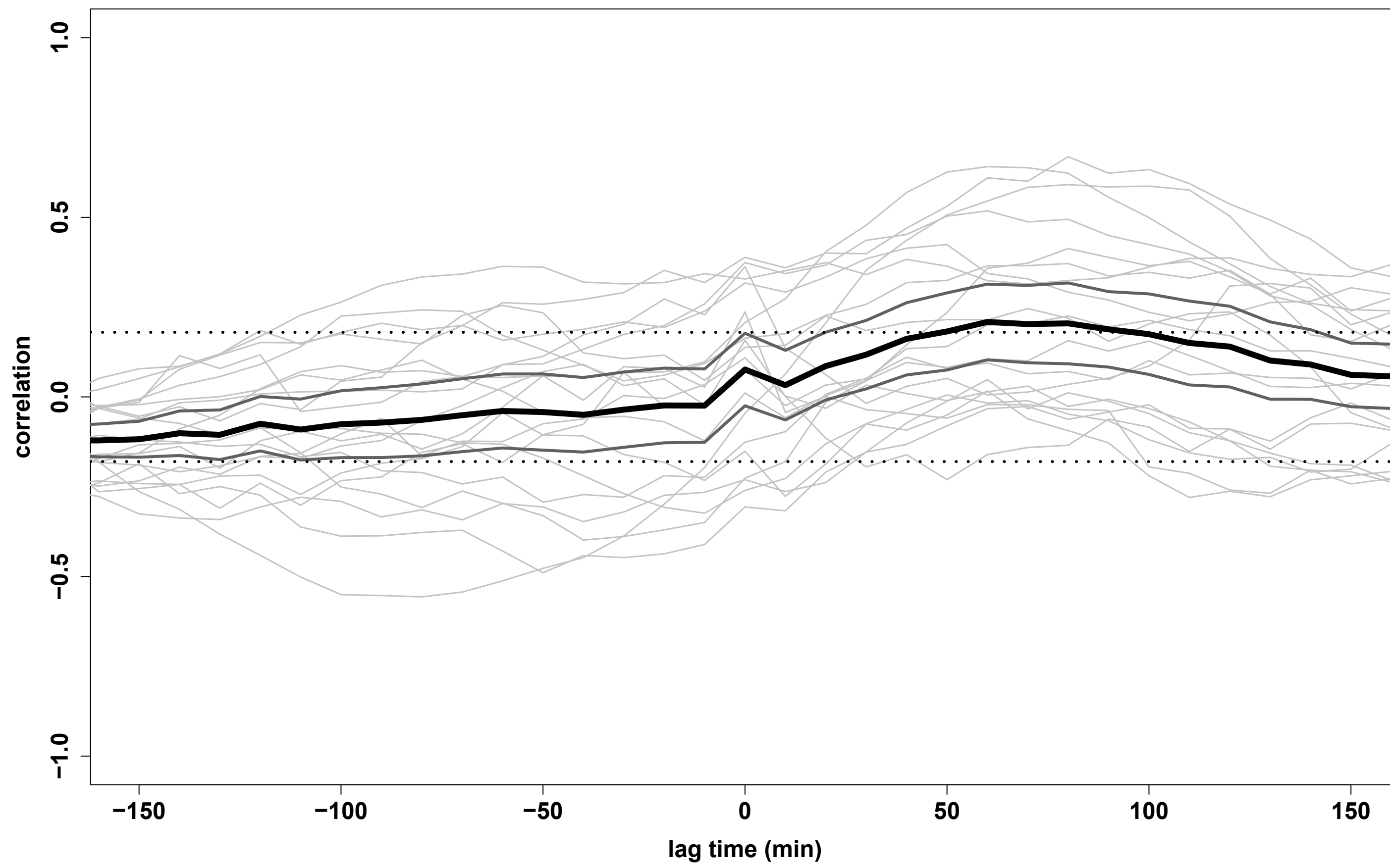
free T concentration



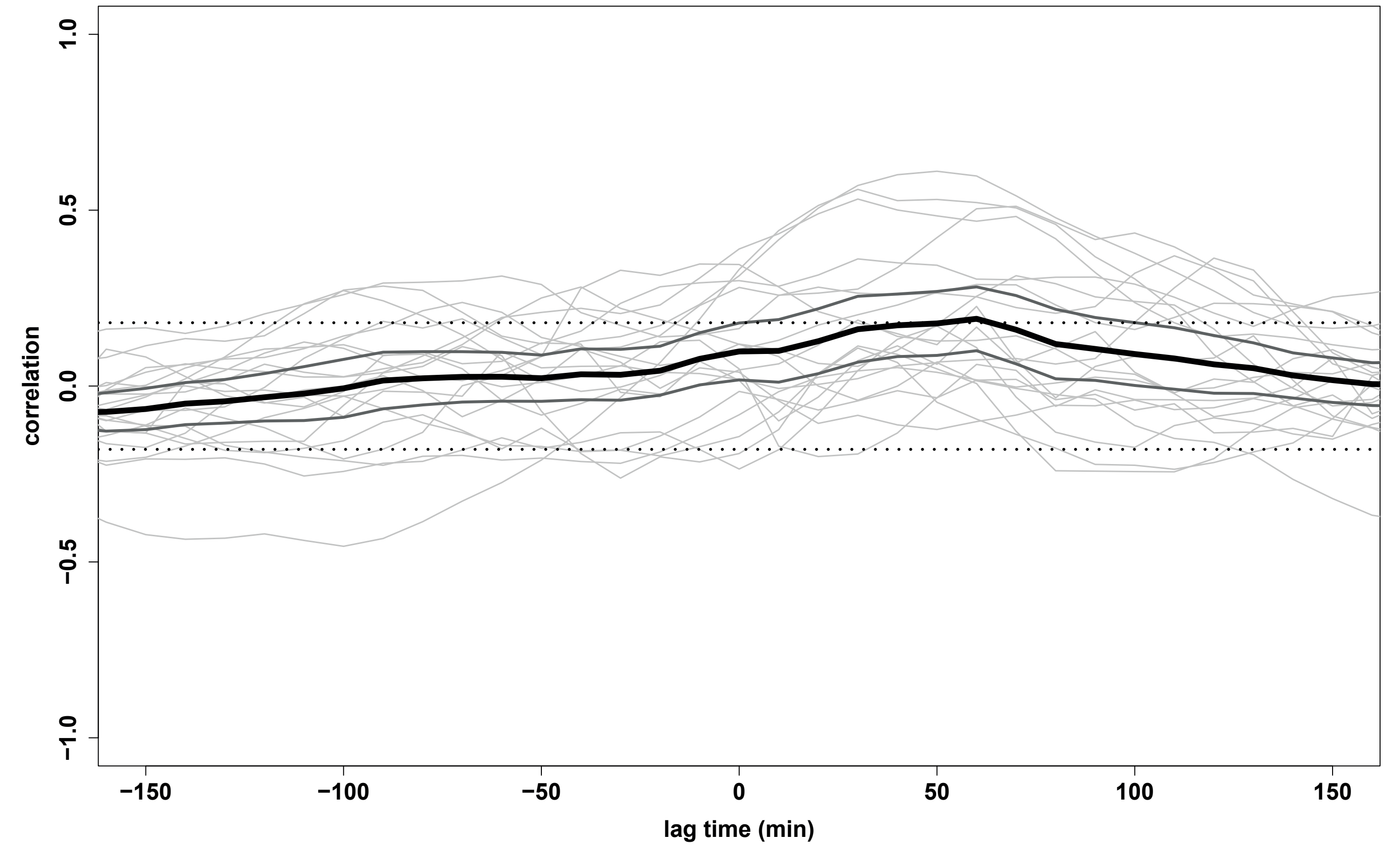
bioavailable T concentration



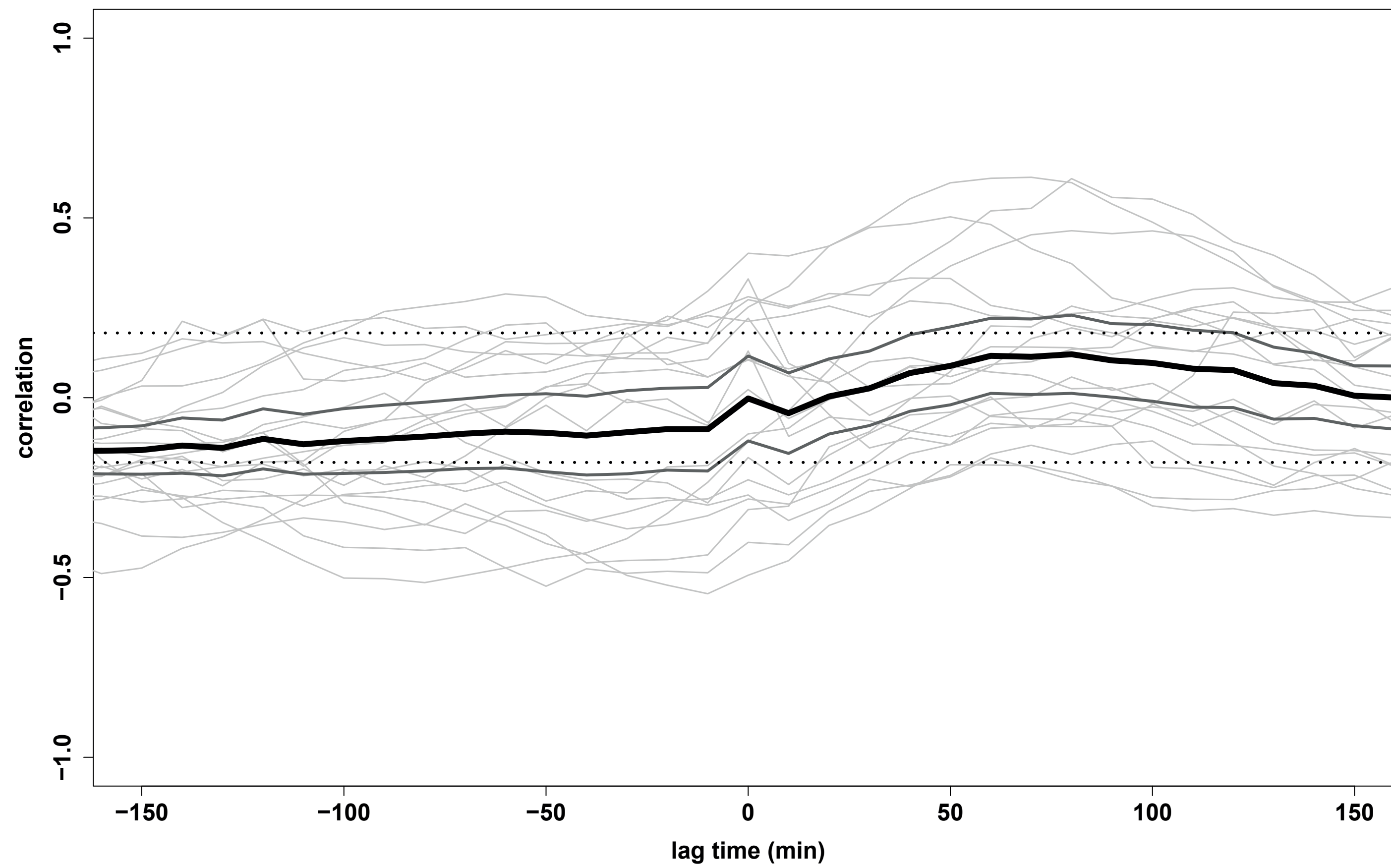
a) LH concentration and total T concentration



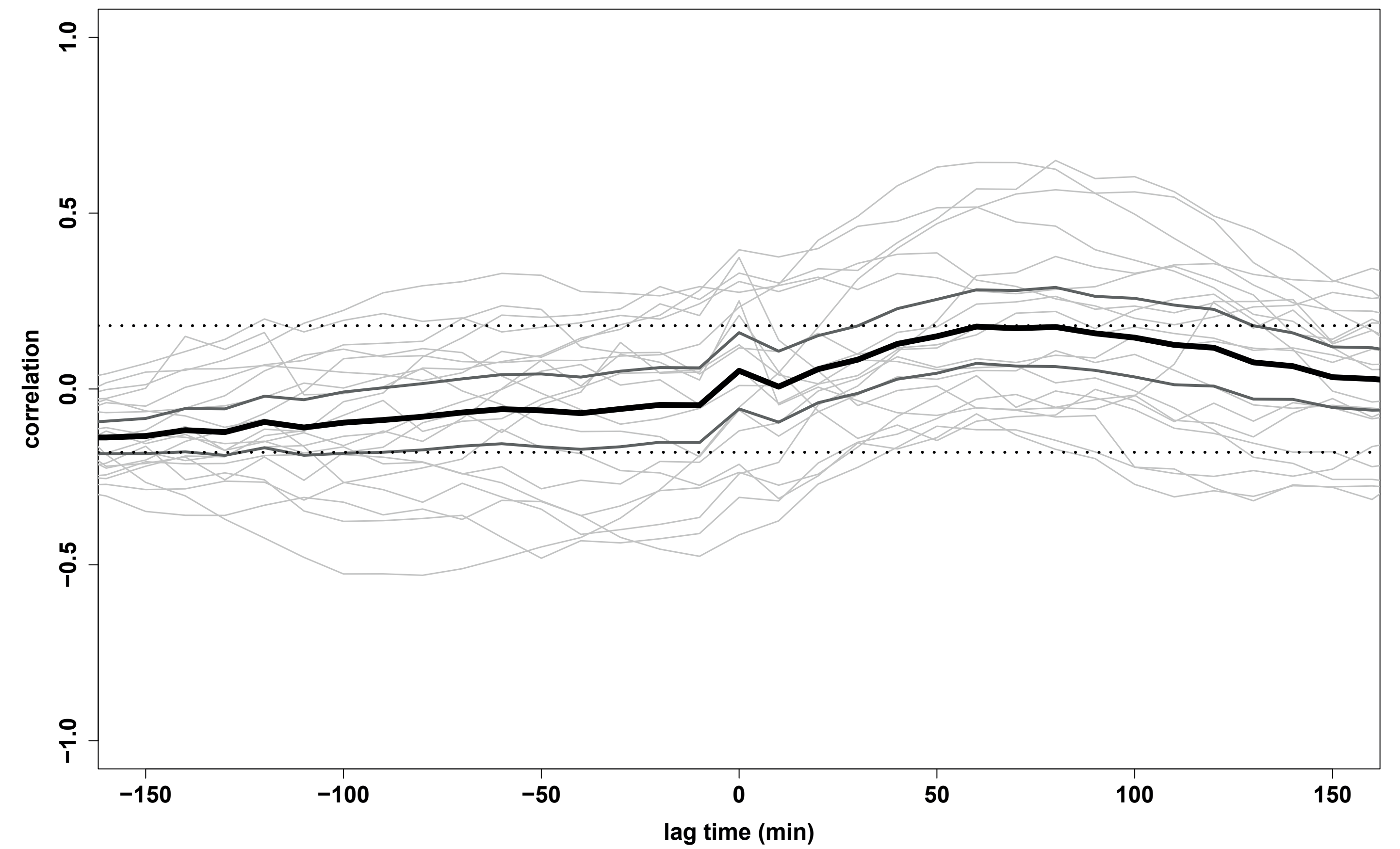
b) LH concentration and T secretion rate

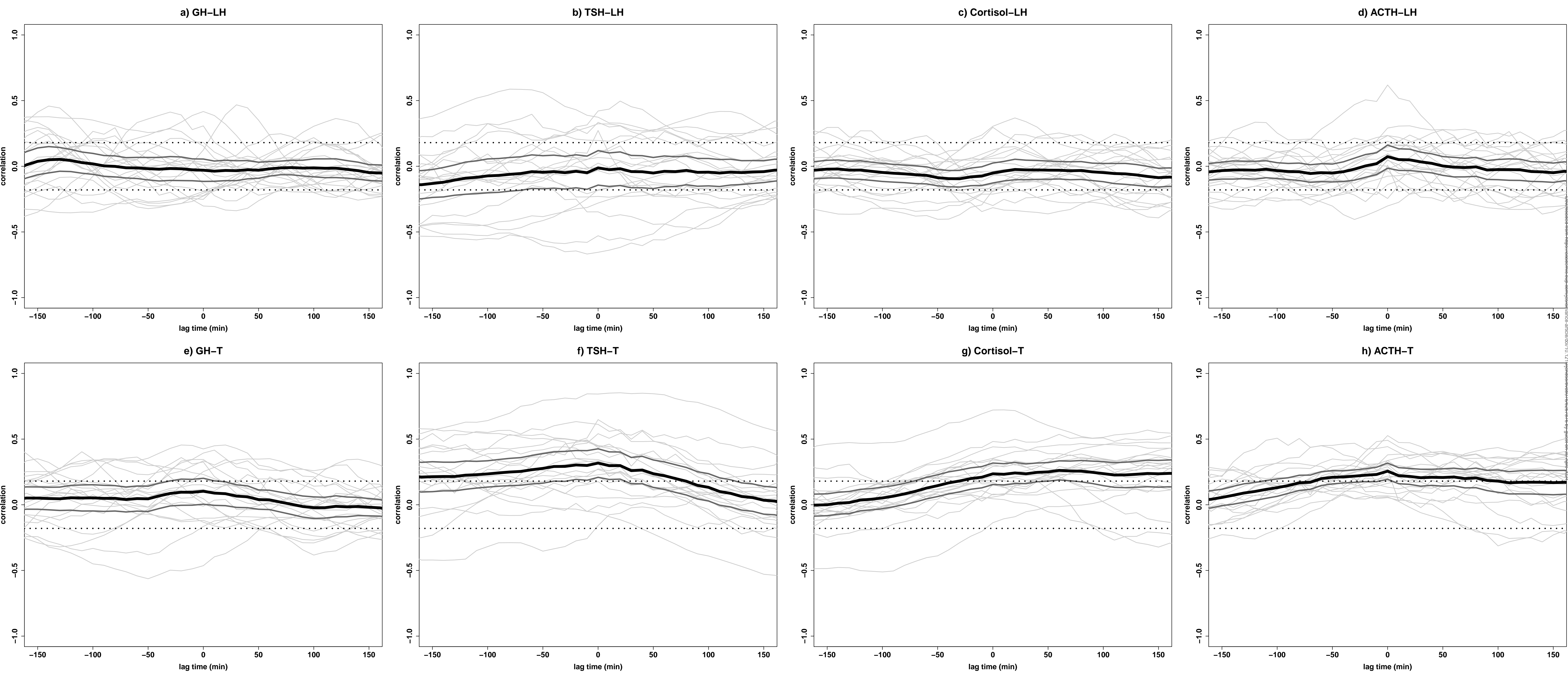


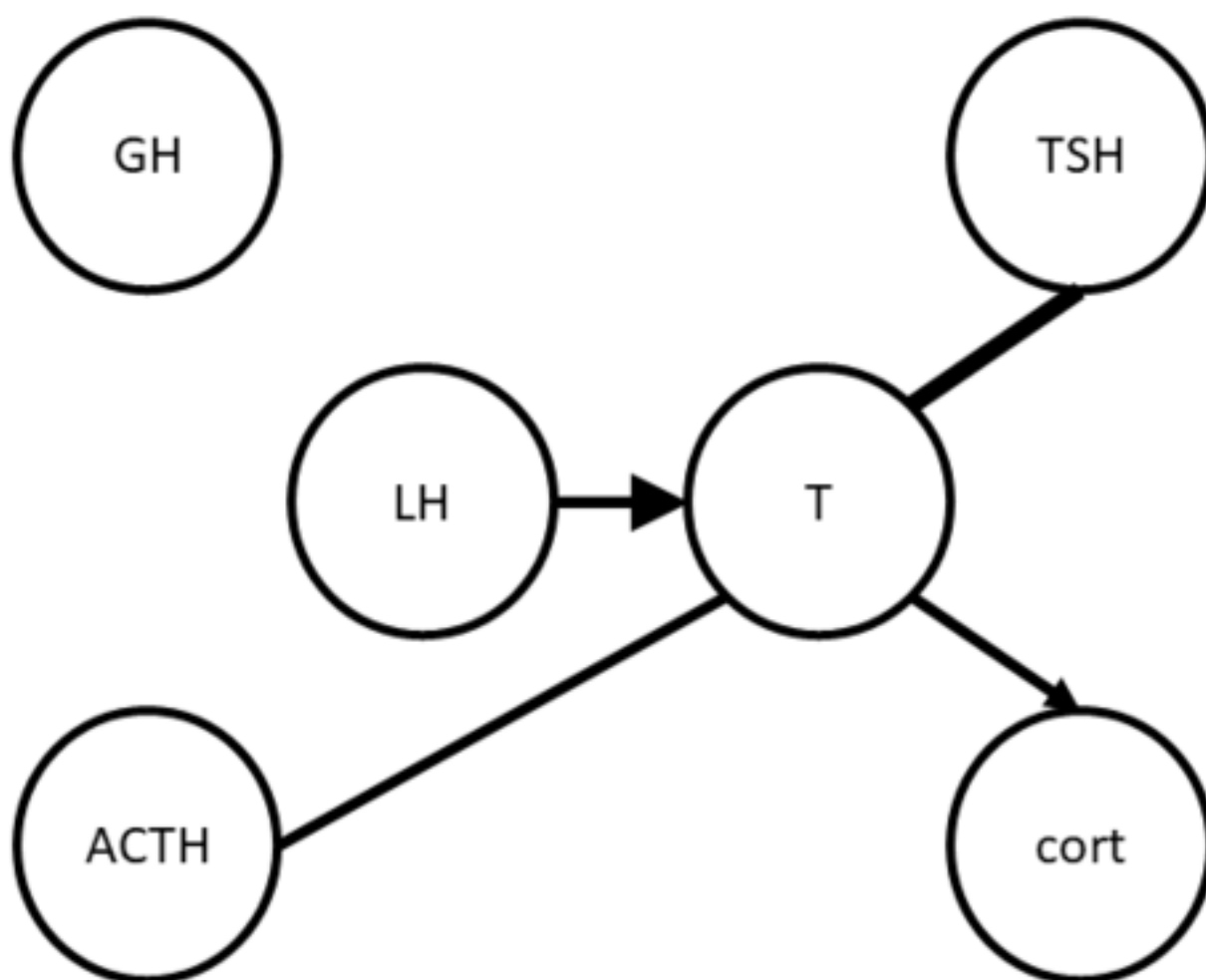
c) LH concentration and free T concentration



d) LH concentration and bioavailable T concentration







→ positive correlation: arrow points in the direction from the leading to the following hormone

— positive correlation: without any delay