Late chronotype is linked to greater cortical thickness in the left fusiform and entorhinal gyri

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ABSTRACT
Humans can be classified as early, intermediate and late chronotypes based on their preferred sleep and wakefulness patterns. Evenness is associated with increased risk of developing several psychiatric conditions, such as major depressive and addictive disorders, however, the anatomical basis of chronotype distinctions, which might predispose to the above conditions, remains largely unexplored. Using magnetic resonance imaging data from 113 healthy young adults (71 females), we aimed to correlate individual chronotype scores with cortical thickness, as well as subcortical and cerebellar grey matter volume. The results revealed one cluster located in the left fusiform and entorhinal gyri showing increased cortical thickness with increasing preference for eveningness. These structures are well positioned to mediate well-established chronotype differences in affective processing, i.e. increased negative affect in late chronotypes. Furthermore, in line with the earlier findings, we found no differences in subcortical and cerebellar grey matter volume. Thus, our study confirms that circadian preference is associated with specific structural cortical substrates and provides a potential anatomical basis for differential affective functioning in morning- and evening-oriented individuals, bridging the gap between brain structure and function.

Introduction
Human physiology is characterised by circadian rhythmicity. These patterns are evident at the cellular, system, and behavioural level (see Vadnie and McClung 2017 for review). The masterminds behind these rhythms are the suprachiasmatic nuclei, a pair of small structures located in the anterior part of the hypothalamus, above the optic chiasm. The circadian system enables temporal synchronisation of body physiology to the environmental cues (as reviewed in Logan and McClung 2019). Humans are known to vary in...
their preferred time of sleep and wakefulness, reflecting differential functioning of the above system. These individual differences in circadian rhythms are known as chronotypes.

Early chronotype (EC) is characterised by earlier hours of waking up, a preference for being active in the morning and earlier hours of going to sleep (J.A. Horne and Ostberg 1976). Conversely, individuals with late chronotype (LC) tend to wake up later in the morning, exhibit more alertness in the afternoon or evening, and display a leaning towards staying up late. An intermediate chronotype (IC), characteristic for the majority of the population, is also distinguished. Chronotype is known to be modulated by age and sex. Children display a preference for morningness, which shifts towards eveningness typology during adolescence and early adulthood, and is followed by the reappearance of EC tendency towards the elderly age (Carrier et al. 1997; Gaina et al. 2006; Fischer et al. 2017). Interestingly, men are more evening-oriented than women, however, the magnitude of the gender differences diminishes with age (Randler and Engelke 2019).

Compared to EC, LC has been linked to differences in a number of physiological variables (Lack et al. 2009) and behavioural domains. Increased negative or decreased positive processing has been observed in LC in tasks probing attentional bias, emotional categorisation, recognition, and recall (Berdyńaj et al. 2016). In addition to this, LC displayed elevated recognition of sad facial expressions (Berdyńaj et al. 2016; C.M. Horne et al. 2016). Furthermore, eveningness has been linked to poorer self-regulation (Digdon and Howell 2008), a higher extent of mood fluctuation (Jeong Jeong et al. 2015), and maladaptive emotion regulation strategies, namely reduced cognitive reappraisal and increased emotion suppression (Watts and Norbury 2017). Additionally, LC display greater drive towards smaller immediate rewards over delayed larger ones (Stolarski et al. 2012; Evans and Norbury 2021). The above mechanisms could explain the reports showing that LC are known to be prone to show more depressive symptoms (Hidalgo et al. 2009; Gaspar-Barba et al. 2009; Au and Reece 2017; Kivelä et al. 2018; Norbury 2021), have been linked to increased substance use, as well as non-substance addictive behaviour, e.g. gambling and compulsive internet use (Lin and Gau 2013; Kervran et al. 2015), and other adaptational problems connected both with their social functioning specificity and physiological characteristics. Despite the growing interest in functional brain imaging research in the field of chronobiology, studies regarding the anatomical differences in the context of chronotype are still lacking. Investigating the neural correlates of varying circadian phenotypes is crucial as it could elucidate the connection between eveningness and psychiatric conditions. Identifying brain structures responsible for the vulnerability of LC for mood and addictive disorders could help create approaches preventing their development, e.g. through applying cognitive strategies known to counteract the changes in structure and function of particular regions.

Studying the human brain structure in vivo is possible by applying magnetic resonance imaging (MRI). Such data represent the brain as a three-dimensional volume or solely the cerebral cortex as a two-dimensional sheet. The volumetric analyses can provide information regarding brain tissue volume or water diffusion (Ashburner and Friston 2000; Le Bihan et al. 2001), whereas the surfaces convey details regarding cortical thickness, surface area, gyrification or sulcal depth (Fischl and Dale 2000; Luders et al. 2006b; Feczko et al. 2007). Investigations into the human brain structure provide us with invaluable insight, helping us to better understand differential nervous system functioning in health
versus disease (Navarṛ et al. 2020), as well as in contrasting phenotypes (S.R. Cox et al. 2019). While several neuroimaging studies have discovered correlations of certain chronotype behavioural features with brain activity (Hasler et al. 2013; C.M. Horne and Norbury 2018b), the literature regarding their anatomical basis is scarce. To the best of our knowledge, there are only three studies in which morphometric grey matter (GM) analyses were conducted in healthy young adults in the context of circadian phenotypes.

Two of the works performed whole-brain analyses. Takeuchi et al. reported that morningness was linked to greater GM volume in the orbitofrontal cortex, whereas eveningness was associated with greater GM values in the precuneus, cuneus, superior parietal lobule, middle occipital lobe, and superior occipital lobe (Takeuchi et al. 2015). These findings were complemented by a study from Rosenberg et al., who showed that EC individuals had smaller GM volume in the lingual gyrus, occipital fusiform gyrus, and occipital pole compared to IC subjects, as well as in the precuneus and lateral occipital cortex compared to LC participants (Rosenberg et al. 2018). In addition to this, they reported EC was associated with a lower cortical thickness than IC in the superior parietal lobe, as well as thinner cerebral cortex than LC in the insula, precuneus, inferior parietal lobe, and pars triangularis. Last but not least, Horne and Norbury investigated chronotype differences in the volume and shape of the hippocampus using a region-of-interest (ROI) approach (C.M. Horne and Norbury 2018a). While no volumetric effects were found, there was a distinction in the shape of the mid-anterior part of the right hemispheric structure. In summary, previous studies have found volume and thickness differences restricted only to the cerebral cortex.

This work aimed to verify these earlier findings and further explore how circadian preference in healthy young adults was related to the cortical thickness, as well as whether distinctions in subcortical and cerebellar GM volume were indeed absent. To our knowledge, this is the first study to perform a correlational analysis between a continuous chronotype measurement and both types of structural brain data on a large dataset.

Materials and methods

Participants

High-resolution structural data were taken from databases of two functional MRI (fMRI) projects (Symfonia 2013/08/W/NZ3/00700 and Harmonia 2013/08/M/HS6/00042). All participants were right-handed, had normal or corrected to normal vision, no neurological and psychiatric disorders, and were drug-free. The history of neurological or psychiatric disorders was self-reported in the selection questionnaire. The additional inclusion criteria comprised: no excessive daytime sleepiness as determined with Epworth Sleepiness Scale (ESS; Johns 1991; Chervin 2003), i.e. ESS ≤ 10; good sleep quality as measured by Pittsburgh Sleep Quality Index (PSQI; Buysse et al. 1989), i.e. PSQI ≤ 5; regular time-of-day schedule without sleep debt (between 6 and 9 hours of sleep per night); no shift work; not having been on a flight passing more than two time zones within the past two months; age between 19 and 35 years. The morningness-eveningness preference of the subjects was assessed with the
Chronotype Questionnaire (ChQ; Oginska 2011; Oginska et al. 2017). The tool consists of 8 items probing an individual’s subjective circadian phase (i.e. morningness-eveningness preference) and 8 questions assessing the subjective amplitude of diurnal variations in mood and activity. Example objects testing circadian preference are “I feel sluggish in the morning and I warm up slowly during the day” and “I am usually in an excellent mood in the morning”. Based on how much a participant agrees with the statement, the item is ranked from 1 to 4. Individual score on the morningness-eveningness scale is calculated as a sum of points from all the questions regarding circadian phase. In the case of our study, the participants’ scores ranged from 11 to 32 (the theoretical range being 8–32 pts.). The higher the score, the more evening-oriented the individual. Similarly to the widely used Morningness-Eveningness Questionnaire (MEQ; J.A. Horne and Ostberg 1976), ChQ treats chronotype as a trait rather than a state. The morningness-eveningness scale of ChQ showed high reproducibility of the results in a two-week test-retest (r = 0.88) and a significant correlation (r = 0.77) between self-assessments in the 7-year interval (Oginska 2011). The scale was also positively validated against MEQ (r = –0.81; Dosseville et al. 2013). The validity of the morningness–eveningness scale was further checked against the external criteria, i.e. the mid-sleep points calculated from reported sleep habits (“real sleep” on regular weekdays) and sleep preferences (“ideal sleep”) – the score correlated positively and significantly with both parameters (Oginska 2011).

All scanning sessions were performed between 5:20 PM and 8:55 PM. This enabled us to control the time-of-day effects on the morphometric measures (Trefler et al. 2016). After visual inspection of the preprocessed MRI data, three participants were excluded from the study due to unsatisfactory removal of non-brain tissue in the segmentation process. Thus, the final sample consisted of 113 subjects (71 females). The summary of the demographic and sleep characteristics of the cohort is provided in Table 1.

All the described analyses were conducted using anonymised data taken from two projects that had been approved by respective ethics committees. Every participant was informed about the procedures and goals of the study they volunteered in and gave their written consent; studies were conducted in accordance with ethical standards described in the Declaration of Helsinki. The dataset used in this investigation has been uploaded to the OpenNeuro repository (Zareba et al. 2021).

| Variable                              | Mean ± standard deviation |
|---------------------------------------|--------------------------|
| Sex (male/female)                     | 42/71                    |
| Age (years)                           | 24.23 ± 3.48             |
| Chronotype Questionnaire              |                          |
| morningness-eveningness scale         | 21.58 ± 5.70             |
| Chronotype Questionnaire              |                          |
| amplitude scale                       | 20.72 ± 3.69             |
| Pittsburgh Sleep Quality Index        | 2.94 ± 1.20              |
| Epworth Sleepiness Scale              | 6.12 ± 2.76              |
Data acquisition

MRI was performed using a 3 T scanner (Magnetom Skyra, Siemens) with a 20-channel or 64-channel head/neck coil. High-resolution anatomical images were acquired using a T1 MPRAGE sequence (176 sagittal slices; 1x1x1.1 mm³ voxel size; TR = 2300 ms, TE = 2.98 ms, flip angle = 9°, GRAPPA acceleration factor 2).

Data analysis

The distribution of the morningness-eveningness scores from the ChQ was tested for normality with the Kolmogorov–Smirnov test. Our data was found to have Gaussian distribution (p = 0.12624), which validated the correlational analyses between the behavioural and structural brain measures. The acquired neuroimaging data was analysed in CAT12 with two different approaches: cortical thickness (Dahnke et al. 2013) and voxel-based morphometry (VBM; Ashburner and Friston 2000). In the case of the cerebral cortex, VBM is known to reflect a combination of thickness, surface area and gyrification measurements, making the data interpretation less straightforward. Based on the above, VBM analysis was restricted only to the subcortical regions and cerebellum.

Cortical thickness analysis

Estimation of cortical thickness in CAT12 was done using the projection-based thickness method. After tissue segmentation, the WM distance was estimated, and the local maxima were then projected onto GM voxels using a neighbouring relationship described by the WM distance. This allowed handling of partial voluming, sulcal blurring, and sulcal asymmetries without explicit sulcus reconstruction. The processing stream subsequently included topology correction, spherical mapping, and spherical registration (Yotter et al. 2011). The resulting cortical thickness meshes in the faverage space were smoothed with a 10-mm Gaussian filter. The statistical analysis was done in SPM12 (Penny et al. 2006). The correlation between the cortical thickness and the morningness-eveningness preference was assessed with one-sample t-tests for all the vertices in the cortex. Sex and age were controlled as covariates. Correction for multiple comparisons was achieved at the cluster level with the family-wise error correction (FWE; p < 0.05) following the initial vertex-wise thresholding (p < 0.001 uncorrected).

Voxel-based morphometry analysis

The default VBM pipeline in CAT12 software was applied, i.e. volumes underwent segmentation of GM, white matter and cerebrospinal fluid, which was followed by spatial normalisation in the standardised MNI152 space using diffeomorphic anatomical registration through exponentiated lie algebra (DARTEL). Normalised GM segments were then modulated using the Jacobian determinant in order to adjust for the resulting volume changes. All preprocessed GM segments were subsequently checked visually to ensure the quality of the process. Lastly, each of the segmented, normalised, and modulated images was smoothed in SPM12 using a 4-mm Gaussian filter. The statistical analysis was performed in AFNI (R.W. Cox 1996) using the 3dMVM program (Chen et al. 2014). The correlation between the tissue volume and
chronotype was calculated with ANCOVA, where sex, age, and total intracranial volume were modelled as covariates. The voxel-wise analysis was restricted to a mask consisting of the following bilateral structures: amygdala, hippocampus, caudate nucleus, globus pallidus, nucleus accumbens, putamen, thalamus, cerebellar cortex and cerebellar vermis. As previously published studies found no chronotype distinctions in the outlined structures in the age group investigated in our work, we performed the correction for multiple comparisons with voxel-level false discovery rate (FDR; \( p < 0.05 \)), setting the minimal cluster forming threshold of 10 voxels. Application of FDR, along with the use of subcortical and cerebellar masks (i.e. reduced number of voxels resulting in fewer statistical tests to be corrected for), should in principle lead to greater power to detect significant findings.

**Results**

**Cortical thickness**

The analysis revealed that the chronotype score was positively correlated with cortical thickness in the left fusiform and entorhinal gyri (\( p < 0.05 \)). The results are depicted in Table 2 and Figures 1–2. The strength of the reported correlation should be, however, treated with caution. Circular analyses, i.e. those that estimate effect size based only on the significant results, like MRI clusters, are known to greatly overestimate the true effect strengths (Kriegeskorte et al. 2010).

| Cluster no. | Coordinates | Vertices | Location | t-stat | Pearson’s correlation r |
|-------------|-------------|----------|----------|--------|-------------------------|
| 1           | −23, −19, −28 | 292      | L fusiform L entorhinal | 4.66   | 0.41                    |

**Figure 1.** Results of the correlational analysis between cortical thickness and chronotype score. One cluster with positive correlation was found in the left fusiform and entorhinal gyri.
Voxel-based morphometry

No correlation between chronotype and GM volume of subcortical regions and cerebellum was found ($p < 0.05$).

Discussion

The cortical thickness analysis revealed that LC had a thicker cortex in the left fusiform and entorhinal gyri compared to EC. Both regions are implicated in processing sensory stimuli. The left fusiform gyrus is an important node in the network responsible for analysing facial information (Zhen et al. 2013), whereas the entorhinal gyrus is a structure integrating sensory input of all modalities (Kerr et al. 2007). Earlier reports have observed increased negative or decreased positive processing in LC individuals across a number of domains, such as attentional bias, emotional categorisation, recognition, and recall independently of poor sleep quality, excessive daytime sleepiness and sleep debt (Kitamura et al. 2010; Simor et al. 2015; Berdynaj et al. 2016). The role of the left fusiform and entorhinal gyri in affective functioning is supported by the Neurosynth database (Yarkoni et al. 2011). A meta-analysis performed with the phrase “negative affect”, which was based on the activations from 97 fMRI studies, has indicated the involvement of a region located on the border of the two aforementioned structures, similar to the site of differences in our examination. In addition to the differences in affective processing, LC was linked to the elevated recognition of sad facial expressions (Berdynaj et al. 2016; C.M. Horne et al. 2016). These findings have been complemented by a report showing increased activity in LC in bilateral amygdalae when viewing fearful faces, which was accompanied by reduced task-related functional connectivity between the right amygdala and dorsal anterior cingulate.

![Figure 2. Correlation between Chronotype Questionnaire score and cortical thickness in the left fusiform and entorhinal gyri.](image)
cortex (C.M. Horne and Norbury 2018b). While the aforementioned study offers one possible explanation for greater reactivity of LC to negative emotional faces, i.e. decreased inhibition of amygdala activity by dorsal anterior cingulate (Etkin et al. 2006; Jhang et al. 2018), the results stemming from our study offer two more potential pathways, which may act convergently with the above mechanism to enhance the activity of the amygdala. Firstly, the lateral nucleus of the amygdala receives high-level sensory input, mainly from the anterior parts of the temporal lobe, including the fusiform gyri (Saygin et al. 2011). Secondly, the entorhinal cortex innervates all amygdalar nuclei (Kerr et al. 2007; Fan et al. 2016). The above implications should be validated by future studies investigating how activity in the left fusiform and entorhinal gyri is linked to negative affect in contrasting chronotypes, as well as works probing how cortical structure corresponds to task-related amygdalar activation during the presentation of negative emotional faces.

Despite using a comparable methodology, i.e. controlling for sleep problems, similar scanning sequences, time of data acquisition and smoothing parameters, we did not find cortical thickness distinctions in any of the areas reported by the earlier work (Rosenberg et al. 2018). One possible explanation lies in the composition of the samples. While our study employed both men and women, only the former were included in the referenced paper, and several studies have revealed distinctions in cortical organisation between males and females (Luders et al. 2006a; Sowell et al. 2007). One limitation of our investigation comes from the use of questionnaires to assess the circadian preference rather than objective measures like cortisol and melatonin rhythms. Nevertheless, a similar approach to determination of chronotype was deployed in the mentioned study, however, both works differed in the tools used to assess chronotype. ChQ deployed in this investigation treats chronotype as a trait, whereas the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al. 2019) used in the study by Rosenberg et al. (2018) perceives it as a state construct. While this methodological difference could be responsible for the discrepancy in findings, ChQ was successfully validated against external criteria, i.e. mid-sleep points calculated from reported sleep habits ("real sleep" on regular weekdays) and sleep preferences ("ideal sleep"). Furthermore, specific structural findings, such as increased GM volume in precuneus of LC, have been reported in healthy young adults regardless of perceiving chronotype as a trait or state (Takeuchi et al. 2015; Rosenberg et al. 2018). Additional difference between the study of ours and the referenced paper stems from treating chronotype measures as continuous or categorical variables. While these two measures correlate with each other (Zavada et al. 2005), arguments have been made that they do not overlap completely. Last but not least, using larger samples, as in our case, should provide a more precise estimation of unknown parameters.

Despite undertaking steps to increase the statistical power, our analyses found no correlation between chronotype and volume of subcortical areas and cerebellum. This result is in line with the previous investigations in healthy young adults (Takeuchi et al. 2015; Rosenberg et al. 2018; C.M. Horne and Norbury 2018a), and suggests that in the discussed age group anatomical chronotype distinctions may be more pronounced in the cerebral cortex than other parts of the brain. This is in contrast to the findings in healthy individuals aged from 40 to 70 recently reported by Norbury (Norbury 2020). In the middle-aged and elderly group with no previous or current psychiatric diagnosis, LC was characterised by increased GM volume in bilateral nucleus accumbens, caudate, putamen, pallidum and thalamus. One explanation for the discrepancy in the sizes of these structures may be that increased volumes in LC in that study reflect the cohort’s resilience to psychiatric disorders,
as e.g. decreased volume of nucleus accumbens has been reported in substance-dependent individuals by a large-scale meta-analysis (Mackey et al. 2018). This inconsistency could, however, also stem from the fact that the discussed paper in the older individuals employed a cohort of 3730 subjects, i.e. far greater than the studies in the young adults and often unreachable for single research units, making it better suited to detect smaller effects. A recently published paper by Evans and colleagues (Evans et al. 2021), which examined volumetric chronotype differences in a lifespan sample of 410 adults aged 18–87, only adds complexity to the above image. The only significant finding reported in the work was the increased volume of the left anterior occipital sulcus in the evening-oriented individuals. In light of the fact that their sample included subjects with past or current psychiatric history, the lack of subcortical differences could speak in favour of the resilience hypothesis regarding the results presented by Norbury (Norbury 2020). However, despite using the ROI approach and a large number of subjects, the study by Evans and colleagues could have also lacked statistical power to detect more subtle subcortical effects. We believe that the remedy to the above considerations could come in the form of performing a large-scale meta-analysis of structural correlates of circadian phenotypes the likes of the work orchestrated by the ENIGMA Consortium (Thompson et al. 2014). The results of such a multicenter investigation can deepen our understanding of the chronotype basis, greatly benefiting the field.

In conclusion, our study revealed that eveningness was associated with increased cortical thickness in the left fusiform and entorhinal gyri, which are well-positioned to be involved in greater negative affect observed in evening-oriented individuals. Our investigation makes a step forward in bridging the gap between brain structure and function in the context of chronotypes.

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Data availability

The dataset analysed during this study has been uploaded to the OpenNeuro repository (ds003826; Zareba et al. 2021).

Disclosure statement

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References

Ashburner J, Friston KJ. 2000. Voxel-based morphometry - the methods. Neuroimage. 11 (6):805–821. doi:10.1006/nimg.2000.0582.

Au J, Reece J. 2017. The relationship between chronotype and depressive symptoms: a meta-analysis. J Affect Disord. 218:93–104. doi:10.1016/j.jad.2017.04.021.

Berdynaj D, Boudissa SN, Grieg MS, Hope C, Mahamed SH, Norbury R. 2016. Effect of chronotype on emotional processing and risk taking. Chronobiol Int. 33(4):406–418. doi:10.3109/07420528.2016.1146739.

Buysse DJ, Reynolds CF 3rd, Monk TH, Berman SR, Kupfer DJ. 1989. The pittsburgh sleep quality index: a new instrument for psychiatric practice and research. Psychiatry Res. 28(2):193–213. doi:10.1016/0165-1781(89)90047-4.

Carrier J, Monk TH, Buysse DJ, Kupfer DJ. 1997. Sleep and morningness-eveningness in the ‘middle’ years of life (20-59 y). J Sleep Res. 6(4):230–237. doi:10.1111/j.1365-2869.1997.00230.x.

Chen G, Adleman NE, Saad ZS, Leibenluft E, Cox RW. 2014. Applications of multivariate modeling to neuroimaging group analysis: a comprehensive alternative to univariate general linear model. Neuroimage. 99:571–588. doi:10.1016/j.neuroimage.2014.06.027.

Chervin RD. 2003. Epworth sleepiness scale. Sleep Med. 4(3):175–176. doi:10.1016/S1389-9457(03)00030-3.

Cox RW. 1996. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. Comput Biomed Res. 29(3):162–173. doi:10.1016/cbmr.1996.0014.

Cox SR, Ritchie SJ, Fawns-Ritchie C, Tucker-Drob EM, Deary IJ. 2019. Structural brain imaging correlates of general intelligence in UK Biobank. Intelligence. 76:101376. doi:10.1016/j.intell.2019.101376.

Dahnke R, Yotter RA, Gaser C. 2013. Cortical thickness and central surface estimation. Neuroimage. 65:336–348. doi:10.1016/j.neuroimage.2012.09.050.

Digdon NL, Howell AJ. 2008. College students who have an eveningness preference report lower self-control and greater procrastination. Chronobiol Int. 25(6):1029–1046. doi:10.1080/07420520802553671.

Dosseville F, Laborde S, Lericollais R. 2013. Validation of a chronotype questionnaire including an amplitude dimension. Chronobiol Int. 30(5):639–648. doi:10.3109/07420528.2012.763042.

Etkin A, Egner T, Peraza DM, Kandel ER, Hirsch J. 2006. Resolving emotional conflict: a role for the rostral anterior cingulate cortex in modulating activity in the amygdala. Neuron. 51(6):871–882. doi:10.1016/j.neuron.2006.07.029.

Evans SL, Leocadio-Miguel MA, Taporoski TP, Gomez LM, Horimoto A, Alkan E, Beijamini F, Pedrazzoli M, Knutson KL, Krieger JE, et al. 2021. Evening preference correlates with regional brain volumes in the anterior occipital lobe. Chronobiol Int. 38(8):1135–1142. doi:10.1080/07420528.2021.1912077.
Evans SL, Norbury R. 2021. Associations between diurnal preference, impulsivity and substance use in a young-adult student sample. Chronobiol Int. 38(1):79–89. doi:10.1080/07420528.2020.1810063.

Fan L, Li H, Zhuo J, Zhang Y, Wang J, Chen L, Yang Z, Chu C, Xie S, Laird AR, et al. 2016. The human brainnetome atlas: a new brain atlas based on connectional architecture. Cerebral Cortex. 26 (8):3508–3526. doi:10.1093/cercor/bhw157.

Feczko E, Augustinack JC, Fischl B, Dickerson BC. 2007. An MRI-based method for measuring volume, thickness and surface area of entorhinal, perirhinal, and posterior parahippocampal cortex. Neurobiol Aging. 30(3):420–431. doi:10.1016/j.neurobiolaging.2007.07.023.

Fischer D, Lombardi DA, Marucci-Wellman H, Roennenberg T. 2017. Chronotypes in the US - influence of age and sex. PLoS One. 12(6):e0178782. doi:10.1371/journal.pone.0178782.

Fischl B, Dale AM. 2000. Measuring the thickness of the human cerebral cortex from magnetic resonance images. Proceedings of the National Academy of Sciences of the United States of America. 97:11044–11049. https://doi.org/10.1073/pnas.200033797.

Gaina A, Sekine M, Kanayama H, Takashi Y, Hu L, Sengoku K, Kagamimori S. 2006. Morning-evening preference: sleep pattern spectrum and lifestyle habits among Japanese junior high school pupils. Chronobiol Int. 23(3):607–621. doi:10.1080/07420520600650646.

Gaspar-Barba E, Calati R, Cruz-Fuentes CS, Ontiveros-Uribe MP, Natale V, De Ronchi D, Serretti AJ. 2009. Depressive symptomatology is influenced by chronotypes. J Affect Disord. 119(1–3):100–106. doi:10.1016/j.jad.2009.02.021.

Hasler BP, Sitnick SL, Shaw DS, Forbes EE. 2013. An altered neural response to reward may contribute to alcohol problems among late adolescents with an evening chronotype. Psyc. Res Neuroimage. 214(3):357–364. doi:10.1016/j.pscychresns.2013.08.005.

Hidalgo MP, Caumo W, Posser M, Coccaro SB, Camozzato AL, Chaves ML. 2009. Relationship between depressive mood and chronotype in healthy subjects. Psychiatry Clin Neurosci. 63 (3):283–290. doi:10.1111/j.1440-1819.2009.01965.x.

Horne CM, Marr-Phillips SDM, Jawaid R, Gibson EL, Norbury R. 2016. Negative emotional biases in late chronotypes. Biol Rhythm Res. 48(1):151–155. doi:10.1080/09291016.2016.1236461.

Horne CM, Norbury R. 2018a. Exploring the effect of chronotype on hippocampal volume and shape: a combined approach. Chronobiol Int. 35(7):1027–1033. doi:10.1080/07420528.2018.1455056.

Horne CM, Norbury R. 2018b. Late chronotype is associated with enhanced amygdala reactivity and reduced fronto-limbic functional connectivity to fearful versus happy facial expressions. Neuroimage. 171:355–363. doi:10.1016/j.neuroimage.2018.01.025.

Horne JA, Ostberg O. 1976. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. Int J Chronobiol. 4(2):97–110.

Jeong Jeong H, Moon E, Min Park J, Lee BD, Lee YM, Choi Y, In Chung Y. 2015. The relationship between chronotype and mood fluctuation in the general population. Psychiatry Res. 229 (3):867–871. doi:10.1016/j.pscychres.2015.07.067.

Jhang J, Lee H, Kang MS, Lee HS, Park H, Han JH. 2018. Anterior cingulate cortex and its input to the basolateral amygdala control innate fear response. Nat Commun. 9(1):2744. doi:10.1038/s41467-018-05090-y.

Johns MW. 1991. A new method for measuring daytime sleepiness: the epworth sleepiness scale. Sleep. 14(6):540–545. doi:10.1093/sleep/14.6.540.

Kerr KM, Agster KL, Furtak SC, Burwell RD. 2007. Functional neuroanatomy of the parahippocampal region: the lateral and medial entorhinal areas. Hippocampus. 17(9):697–708. doi:10.1002/hipo.20315.

Kervran C, Fatséas M, Serre F, Taillard J, Beltran V, Leboucher J, Debrabant R, Alexandre JM, Daulouède JP, Philip P, et al. 2015. Association between morningness/eveningness, addiction severity and psychiatric disorders among individuals with addictions. Psychiatry Res. 229 (3):1024–1030. doi:10.1016/j.psychres.2015.05.026.

Kitamura S, Hida A, Watanabe M, Enomoto M, Aritake-Okada S, Moriguchi Y, Kamei Y, Mishima K. 2010. Evening preference is related to the incidence of depressive states independent of sleep-wake conditions. Chronobiol Int. 27(9–10):1797–1812. doi:10.3109/07420528.2010.516705.
Kivelä L, Papadopoulos MR, Antypa N. 2018. Chronotype and psychiatric disorders. Curr Sleep Med Repor. 4(2):94–103. doi:10.1007/s40675-018-0113-8.

Kriegeskorte N, Lindquist MA, Nichols TE, Poldrack RA, Vul E. 2010. Everything you never wanted to know about circular analysis, but were afraid to ask. J Cerebral Blood Flow Meta. 30(9):1551–1557. doi:10.1038/jcbfm.2010.86.

Lack L, Bailey M, Lovato N, Wright H. 2009. Chronotype differences in circadian rhythms of temperature, melatonin, and sleepiness as measured in a modified constant routine protocol. Nat Sci Sleep. 1:1–8. doi:10.2147/nss.s6234.

Le Bihan D, Mangin JF, Poupon C, Clark CA, Pappata S, Mollo N, Chabriat H. 2001. Diffusion tensor imaging: concepts and applications. J Magn Res Imag. 13(4):534–546. doi:10.1002/jmri.1076.

Lin YH, Gau SSF. 2013. Association between morningness–eveningness and the severity of compulsive internet use: the moderating role of gender and parenting style. Sleep Med. 14 (12):1398–1404. doi:10.1016/j.sleep.2013.06.015.

Logan RW, McClung CA. 2019. Rhythms of life: circadian disruption and brain disorders across the lifespan. Nat Rev Neurosci. 20:49–65. doi:10.1038/s41583-018-0088-y.

Luders E, Narr KL, Thompson PM, Rex DE, Woods RP, Deluca H, Jancke L, Toga AW. 2006a. Gender effects on cortical thickness and the influence of scaling. Hum Brain Mapp. 27(4):314–324. doi:10.1002/hbm.20187.

Luders E, Thompson PM, Narr KL, Toga AW, Jancke L, Gaser C. 2006b. A curvature-based approach to estimate local gyriﬁcation on the cortical surface. Neuroimage. 29(4):1224–1230. doi:10.1016/j.neuroimage.2005.08.049.

Mackey S, Allgaier N, Chaarani B, Spechler P, Orr C, Bunn J, Allen NB, Alia-Klein N, Batalla A, Blaine S, ENIGMA Addiction Working Group, et al. 2018. Mega-analysis of gray matter volume in substance dependence: general and substance-speciﬁc regional effects. Amer J Psyc. 176(2):119–128. doi:10.1176/appi.ajp.2018.17040415.

Navarri X, Afzali M, Lavoie J, Sinha R, Stein D, Momenan R, Veltman D, Korucuoglu O, Sjoerds Z, Van Holst R, et al. 2020. How do substance use disorders compare to other psychiatric conditions on structural brain abnormalities? A cross-disorder meta-analytic comparison using the ENIGMA consortium ﬁndings. Hum Brain Mapp. 1–15. doi:10.1002/hbm.25114.

Norbury R. 2020. Diurnal preference and grey matter volume in a large population of older adults: data from the UK Biobank. J Circadian Rhythms. 18(1):3. doi:10.5334/jcr.193.

Norbury R. 2021. Diurnal preference and depressive symptomatology: a meta-analysis. Sci Rep. 11 (1):12003. doi:10.1038/s41598-021-91205-3.

Oginska H. 2011. Can you feel the rhythm? A short questionnaire to describe two dimensions of chronotype. Pers Individ Dif. 50(7):1039–1043. doi:10.1016/j.paid.2011.01.020.

Oginska H, Mojsa-Kaja J, Mairesse O. 2017. Chronotype description: in search of a solid subjective amplitude scale. Chronobiol Int. 34(10):1388–1400. doi:10.1080/07420528.2017.1372469.

Penny W, Friston KJ, Ashburner J, Kiebel S, Nichols T. 2006. Statistical Parametric Mapping: the Analysis of Functional Brain Images. 1st Edition. Cambridge, MA: Academic Press.

Randler C, Engelke J. 2019. Gender differences in chronotype diminish with age: a meta-analysis based on morningness/chronotype questionnaires. Chronobiol Int. 36(7):888–905. doi:10.1080/07420528.2019.1585867.

Roenneberg T, Pilz LK, Zerbini G, Winnebeck EC. 2019. Chronotype and social jetlag: a (self-) critical review. Biology. 8(3):54. doi:10.3390/biology8030054.

Rosenberg J, Jacobs HI, Maximov II, Reske M, Shah NJ. 2018. Chronotype differences in cortical thickness: grey matter reﬂects when you go to bed. Brain Struct Funct. 223(7):3411–3421. doi:10.1007/s00429-018-1697-y.

Saygin ZM, Osher DE, Augustinack J, Fischl B, Gabrieli JD. 2011. Connectivity-based segmentation of human amygdala nuclei using probabilistic tractography. Neuroimage. 56(3):1353–1361. doi:10.1016/j.neuroimage.2011.03.006.

Simor P, Zavecz Z, Pálosi V, Török C, Köteles F. 2015. The inﬂuence of sleep complaints on the association between chronotype and negative emotionality in young adults. Chronobiol Int. 32 (1):1–10. doi:10.3109/07420528.2014.935786.
Sowell ER, Peterson BS, Kan E, Woods RP, Yoshii J, Bansal R, Xu D, Zhu H, Thompson PM, Toga AW. 2007. Sex differences in cortical thickness mapped in 176 healthy individuals between 7 and 87 years of age. Cerebral Cortex. 17(7):1550–1560. doi:10.1093/cercor/bhl066.

Stolarski M, Ledzinska M, Matthews G. 2012. Morning is tomorrow, evening is today: relationships between chronotype and time perspective. Biol Rhythm Res. 44:1–16. doi:10.1080/09291016.2012.656248.

Takeuchi H, Taki Y, Sekiguchi A, Nouchi R, Kotozaki Y, Nakagawa S, Miyauchi CM, lizuka K, Yokoyama R, Shinada T, et al. 2015. Regional gray matter density is associated with morningness-eveningness: evidence from voxel-based morphometry. Neuroimage. 117:294–304. doi:10.1016/j.neuroimage.2015.05.037.

Thompson PM, Stein JL, Medland SE, Hibar DP, Vasquez AA, Renteria ME, Toro R, Jahanshad N, Schumann G, Franke B, Saguenay Youth Study (SYS) Group, et al. 2014. The ENIGMA consortium: large-scale collaborative analyses of neuroimaging and genetic data. Brain Imaging Behav. 8 (2):153–182. doi:10.1007/s11682-013-9269-5.

Trefler A, Sadeghi N, Thomas AG, Pierpaoli C, Baker CI, Thomas C. 2016. Impact of time-of-day on brain morphometric measures derived from T1-weighted magnetic resonance imaging. Neuroimage. 133:41–52. doi:10.1016/j.neuroimage.2016.02.034.

Vadnie C, McClung CA. 2017. Circadian rhythm disturbances in mood disorders: insights into the role of the suprachiasmatic nucleus. Neural Plast. 2017:1–28. doi:10.1155/2017/1504507.

Watts AL, Norbury R. 2017. Reduced effective emotion regulation in night owls. J Biol Rhythms. 32 (4):369–375. doi:10.1177/074771717709111.

Yarkoni T, Poldrack RA, Nichols TE, Van Essen DC, Wager TD. 2011. Large-scale automated synthesis of human functional neuroimaging data. Nat Methods. 8(8):665–670. doi:10.1038/nmeth.1635.

Yotter RA, Dahnke R, Thompson PM, Gaser C. 2011. Topological correction of brain surface meshes using spherical harmonics. Hum Brain Mapp. 32(7):1109–1124. doi:10.1002/hbm.21095.

Zareba MR, Fafrowicz M, Marek T, Beldzik E, Oginska H, Domagalki A. 2021. Structural (t1) images of 113 young healthy adults; study of effects of chronotype on brain structure. OpenNeuro. doi:10.18112/openneuro.ds003826.v1.0.0.

Zavada A, Gordijn MCM, Beersma DGM, Daan S, Roenneberg T. 2005. Comparison of the munich chronotype questionnaire with the Horne-Östberg’s morningness-eveningness score. Chronobiol Int. 22(2):267–278. doi:10.1081/CBI-200053536.

Zhen Z, Fang H, Liu J. 2013. The hierarchical brain network for face recognition. PLoS One. 8(3): e59886. doi:10.1371/journal.pone.0059886.

Int. chronotype doi:113 usiing of (4):369–375.