

Age-related differences in the functional topography of the locus coeruleus: implications for cognitive and affective functions

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Abstract

The locus coeruleus (LC) is an important noradrenergic nucleus that has recently attracted a lot of attention because of its emerging role in cognitive and psychiatric disorders. Although previous histological studies have shown that the LC has heterogeneous connections and cellular features, no studies have yet assessed its functional topography in vivo, how this heterogeneity changes over aging and whether it is associated with cognition and mood. Here we employ a gradient-based approach to characterize the functional heterogeneity in the organization of the LC over aging using 3T resting-state fMRI in a population-based cohort aged from 18 to 88 years old (Cambridge Centre for Ageing and Neuroscience cohort, $n=618$). We show that the LC exhibits a rostro-caudal functional gradient along its longitudinal axis, which was replicated in an independent dataset (Human Connectome Project 7T dataset, $n=184$). Although the main rostro-caudal direction of this gradient was consistent across age groups, its spatial features varied with increasing age, emotional memory and emotion regulation. More specifically, a loss of rostral-like connectivity, more clustered functional topography and greater asymmetry between right and left LC gradients was associated with higher age and worse behavioral performance. Furthermore, participants with higher-than-normal Hospital Anxiety and Depression Scale ratings exhibited alterations in the gradient as well, which manifested in greater asymmetry. These results provide an in vivo account of

how the functional topography of the LC changes over aging, and imply that spatial features of this organization are relevant markers of LC-related behavioral measures and psychopathology.

eLife assessment

This study provides **fundamental** imaging evidence from two independent functional imaging datasets, for a rostral-caudal gradient of locus coeruleus connectivity, which changes across the lifespan. The gradient approach is well-established and **convincing** results were obtained and validated using large 3T and 7T fMRI datasets. This work will be of interest to clinical and cognitive neuroscientists.

Introduction

The central noradrenergic system comprises projections to widespread cortical and subcortical areas of the brain, with important neuromodulatory roles in sleep and arousal, executive function, mood, emotion regulation and memory (1). Most of the noradrenergic transmission in the brain originates from the locus coeruleus (LC), a bilateral nucleus in the dorsolateral pons. The LC has been implicated in aging-related cognitive changes and neurodegenerative conditions, such as Alzheimer's disease (AD) or Parkinson's disease (PD) (2). Interestingly, different conditions seem to affect different parts of the LC (3,4), and several studies show that subregions of the LC might be involved in different cognitive functions and psychiatric symptoms (5,6). Specifically, the rostral part is associated with memory and emotion regulation, being often affected in AD (5–8), whereas the integrity of the caudal part has been linked to more general cognitive processes in PD (4,9).

However, a dichotomous functional division model of the LC might be oversimplistic, and technical difficulties concerning imaging of the LC (such as low spatial resolution of functional imaging techniques, inconvenient anatomical location or noise from adjacent cerebrospinal fluid spaces (10)) could hide a more complex underlying functional organization. Additionally, multiple overlapping axes of functional organization might be present that can confound current traditional cluster-based models that seek to divide the LC into subregions (11,12). Similar issues have been raised regarding other subcortical nuclei, where researchers started to unravel this complexity by modeling voxel-wise functional organization with a gradient-based approach. For example, several studies reported that the hippocampus is organized by a gradient of connectivity profiles and microstructural properties along its longitudinal axis (13). These spatial characteristics of hippocampal gradients explained individual differences in behavior better than a cluster-based model, and therefore provided a closer approximation to the true organization profile of this region. Other studies investigated gradients of functional connectivity in the striatum in healthy individuals and patients with PD. Haak et al. found that, apart from the primary functional connectivity gradient, a second axis of connectopic organization was present in the striatum that closely resembled the spatial distribution of dopamine transporters across different medication and symptomatology stages, providing a non-invasive marker for striatal dopamine transporter density in PD (14). To our knowledge, so far, no studies have investigated the functional gradients of the LC. This is important because this region modulates various behavioral functions and widespread brain regions in a very precise manner (15). Furthermore, studies using fMRI to describe connectivity in the LC report heterogeneous results – possibly because the localization methods, the studied populations and preprocessing pipelines often differ (16–19) – and a similarity gradient-based approach might be better suited to characterize its functional organization by mitigating the effect of heterogeneous individual differences in

connectivity and imaging acquisition-related noise, since it is less affected by e.g. ROI inaccuracies (20 [↗](#)). The aims of our study were to: 1) identify the functional gradients of the LC and reproduce them across different cohorts and image resolutions, using a 3T (the Cambridge Centre for Ageing and Neuroscience or CamCAN cohort) and a 7T (the Human Brain Connectome or HCP 7T cohort) datasets; 2) characterize how the functional gradients of the LC change over the course of aging in the CamCAN dataset, a large cohort of 618 individuals with resting-state fMRI between 18 and 88 years old; 3) identify LC projections to cortical and subcortical areas; and 4) detect relevant associations between LC gradients with cognitive, emotional/affective and physiological functions that decline with increasing age.

We show that the LC exhibits a basic rostro-caudal functional gradient that is reproducible across different cohorts and age-ranges. The LC functional gradient is driven by different patterns of connections to cortical and subcortical areas that are relevant to understand the pathophysiological mechanisms of neurodegenerative disorders. Moreover, we demonstrate that individual differences in the finer spatial layout of the rostro-caudal gradient are related to age, and functions ascribed to the noradrenergic system correlate with gradient spatial characteristics when corrected for the effects of age. Our findings provide an alternative model of LC functional organization that might explain why distinct functional alterations of the LC could lead to different cognitive and psychiatric disorders.

Materials and methods

Participants

We included 618 participants who had resting-state fMRI data from the CamCAN dataset (<https://www.cam-can.org> [↗](#)). To investigate the relationship between LC functional gradients and cognitive measures, we assessed a set of cognitive functions that were previously associated with LC function (15 [↗](#)), namely negative valence trials of emotional memory and emotion regulation tests (5 [↗](#)), executive functions measured by the Hotel-task (21 [↗](#)), sleep quality measured by the Pittsburgh Sleep Quality Index (PSQI) (22 [↗](#)) as well as anxiety and depression symptoms measured by the Hospital Anxiety and Depression Scale (HADS) (23 [↗](#)). From the imaging dataset, 292 participants had emotional memory scores, 272 emotion regulation scores, 601 Hotel-task scores, 586 PSQI scores and 615 had HADS scores. Demographic characteristics of these subgroups did not differ from that of the whole sample. To investigate the reproducibility of the functional gradient results, we analyzed 184 participants from the Human Connectome Project (HCP) with 7T resting-state fMRI data (<https://db.humanconnectome.org> [↗](#)). The first resting-state fMRI run was analyzed for all subjects.

Image acquisition

The 3T resting-state fMRI protocol for the CamCAN dataset included an echo planar imaging (EPI) sequence (TR=1970 ms; TE=30 ms; FOV: 192×192 mm; 3×3×4.4 mm³ voxel resolution; duration: 8.5 minutes); data was collected at a single site using a 3T Siemens TIM Trio scanner with a 32-channel head coil (24 [↗](#)). Participants were asked to lie motionless with their eyes closed and not fall asleep during the scan.

The acquisition protocol for the HCP 7T resting-state fMRI data included a multiband gradient-echo EPI sequence (TR=1000 ms; TE=22.2 ms; FOV: 208×208 mm; 1.6 mm isotropic voxel resolution; duration: 16 minutes); data was collected at a single site using a 7T Siemens Magnetom scanner (25 [↗](#)). During the acquisition, participants were asked to keep their eyes open and fixate on a cross, shown on a presentation screen inside the scanner.

Image pre-processing

The HCP 7T dataset was preprocessed according to a minimal preprocessing pipeline as described in (26). First, fMRI scans underwent EPI distortion correction, removal of non-brain tissue, motion correction, intensity normalization and a two-stage registration to standard MNI space, followed by regression of noise and motion-related artifacts using FSL FIX (<https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FIX>) and high-pass filtering with a cut-off of 2000s. Additionally, following previous publications using functional gradients (13,20), signals from the cerebrospinal fluid and white matter were removed via nuisance regression.

Functional scans from the CamCAN dataset were preprocessed through a standard pipeline implemented in fMRIPrep (v20.2.4). After removing the first two volumes to allow for steady state magnetization, functional images were corrected for motion and slice timing effects, skull-stripped and co-registered to a standard 2 mm resolution MNI152 template space using a two-stage registration approach with Freesurfer (27) and ANTs (28). Nuisance regression was performed to further correct for motion effects (employing the 24-parameter head motion model (29)) and to remove confounding signals from the cerebrospinal fluid and white matter.

To minimize signal leakage from the surrounding brainstem regions and the fourth ventricle, the LC was masked for each subject and spatial smoothing was applied with a 3 mm FWHM isotropic 3D Gaussian kernel within the mask to ensure that weighted graphs obtained from the similarity matrices are fully connected, since a measure of spatial smoothness is necessary for gradient calculation ((20); see Connectopic mapping section).

Delineation of the locus coeruleus

The locus coeruleus was delineated using a standard mask from a recent study that developed a meta-analytical consensus mask by aggregating previous segmentations of the LC on neuromelanin-sensitive MRI sequences (30). The mask was transformed to standard MNI152 space and downsampled to the respective isotropic spatial resolution of the two preprocessed datasets (2 mm isotropic voxels in the Cam-CAN dataset and 1.6 mm isotropic voxels in the HCP 7T dataset).

Connectopic mapping

After preprocessing, we performed connectopic mapping, a data-driven approach that characterizes spatially continuous changes in connectivity profiles as gradients (20), using the ConnGrads toolbox (<https://github.com/koenhaak/congrads>). The analysis starts by calculating functional connectivity matrices (or “fingerprints”) between all voxel time series in a region of interest (ROI; in this case this was the LC defined in the way described above), and time series from a target mask. In the current study, the target mask was defined using a cortical and subcortical parcellation. Average time series were extracted from each parcel in the atlases separately, and then pairwise correlations were calculated with timeseries from all voxels in the ROI (the LC). We used the Glasser-atlas (containing 360 parcels) as cortical and the Tian-atlas (containing 50 parcels) as subcortical parcellation (31,32). Afterwards, we obtained a similarity matrix from the functional connectivity matrices of LC ROI voxels by calculating the eta-squared measure (33). The similarity matrix contains the eta-squared similarity measure of fingerprints between all pairs of LC voxels, therefore one index in the similarity matrix corresponds to the similarity between the fingerprints of two specific LC voxels. This similarity matrix was then transformed into a connected graph and fed to the Laplacian eigenmaps algorithm (34), which results in a decomposition of the similarity graph so that the eigenvectors of graph Laplacian represent axes along which the step-wise change in functional connectivity is the largest, i.e. spatially graded patterns of functional organization, or functional gradients. Along these gradients, voxels which exhibit similar functional connectivity fingerprints will be placed close to each other. The spatial features of these gradients were then summarized using a spatial regression approach (trend surface modeling) to improve sensitivity over voxel-wise analyses.

Trend surface modeling uses polynomial basis functions to describe the spatial features of a functional gradient (35). We fit a third-order trend surface model (TSM) based on previous studies (13,14,36) that contains nine parameters corresponding to the three axes of MNI152 space using Bayesian linear regression (coefficients for x, y, z axes and their second and third power: x^2 , y^2 , z^2 , and x^3 , y^3 , z^3). More generally speaking, first order coefficients of the TSM describe the slope of changes in functional connectivity along the x, y, z axes, while higher order coefficients describe more detailed spatial features (such as curvature).

Statistical analysis

Statistical analysis was performed using RStudio (v2022.07.1, with the *rsq* package, v2.5: <https://cran.r-project.org/package=rsq>) and MATLAB (MathWorks Inc., R2021B). Since individual gradient estimation is often not consistent (20), we derived a group-based scheme to estimate the relationship between behavioral variables and LC gradient parameters. To estimate the relationship between the gradients and age, we estimated average gradients for each year (from 18 to 88 years) and calculated their association with increasing age using Spearman's partial rank correlation coefficients.

To assess how continuous cognitive scores are related to the gradients we employed a sliding window correlation approach. More specifically, participants were sorted into ascending order based on the cognitive test. Then, an average gradient and cognitive score, as well as nuisance variables were calculated for a window of subjects. Here we chose a window length of 20 subjects to preserve statistical power for the correlations while also making sure that the gradient estimation was consistent. The window was then slid in steps of 5 subjects, and the procedure was repeated for all windows. The resulting window-averaged values were then included in a linear model and F-tests were used to compare the linear model that included the gradient spatial model parameters and nuisance variables to a null model containing only nuisance variables, similarly to previous studies that used connectopic mapping (13). The partial coefficient of determination from the F-tests was calculated to obtain explained variance of the first model over and above the effects of nuisance variables. Additionally, Spearman's partial rank correlation was calculated between the windowed gradient parameters and cognitive scores, controlling for the effects of age, sex and education to see if parameters of the spatial model could be used as specific markers of cognitive performance. For the F-tests and post-hoc correlations, false discovery rate (FDR) corrections were applied to correct for multiple comparisons.

Furthermore, to check how the clusterability of the gradient (i.e., how clearly the rostral and caudal region differs in terms of connectivity), we carried out the following analysis based on (37). Gradient maps were clustered into $k=2$ clusters using the k-means clustering algorithm, then the Calinski-Harabasz criterion was calculated for each individual gradient map, which was then used as a measure of clusterability and correlated with age by calculating the partial Spearman's rank correlation coefficient controlling for the effects of sex.

The Hospital Anxiety and Depression Scale was used to stratify the participants into people with and without depressive and anxiety symptoms (HADS anxiety and/or depression scores below and above 7 (23)). Since the resulting groups were highly imbalanced (499 participants with normal, 116 with abnormal HADS scores), we performed bootstrapping to obtain an equal sized sample of group average gradients (drawing 20 subjects for each iteration) from the two groups. Spatial model parameters were compared between the two groups using a one-way multivariate analysis of variance (MANOVA). Afterwards, post-hoc Mann-Whitney U-tests were carried out for each spatial model parameter. Correction for multiple comparisons was performed via FDR.

Functional connectivity is organized along a rostro-caudal axis in the locus coeruleus

Characteristics of both cohorts can be found in [Table 1](#). The average dominant gradient consistently exhibited a rostro-caudal organization in all age groups in the CamCAN dataset and across all subjects in the HCP 7T dataset (see [Figure 1A](#); also see Supplementary Material, [Figure S2](#) for a difference map of gradients from the two datasets). To assess the extent to which the ROI mask influences the rostro-caudal gradient, we repeated the gradient calculation in both datasets using a larger LC ROI from [\(38\)](#); gradients using this ROI retained the rostro-caudal organization (see Supplementary Material, [Figure S3](#)). The gradient was monotonous, meaning that the stepwise changes in connectivity were consistent along the longitudinal axis of the LC and did not show clear functional area boundaries. When partitioned into rostral and caudal parts, the rostral part was characterized by connections to the posterior and anterior cingulate cortices and the medial temporal lobe, whereas the caudal part projected to the parietal and visual cortices. Regarding subcortical structures, the rostral LC mainly projected to the hippocampi, amygdalae and striatum, while the caudal part projected to the thalami, occipital, precentral and postcentral regions (see [Figure 1B](#)). To summarize, the rostral part was mainly associated with higher order, associative cortical areas and limbic regions, while the caudal part was more connected to primary sensorimotor and visual areas.

The functional gradient in the locus coeruleus is different across ages

The gradient explained a significant amount of variance in age over and above the effects of sex ($F = 8.671$, adjusted partial $R^2 = 0.504$, $p < 0.001$; see [Figures 2A](#) and [2B](#)). Also, specific parameters of the gradient's spatial model were associated with age in a way that a loss of rostral-like connectivity, more clustered appearance and increased asymmetry were related with older age (see correlation plots on [Figure 2B](#)). This was further confirmed by the clusterability analysis, which showed that, with increasing age, the gradient could be clustered into rostral and caudal regions more effectively ($R=0.313$, $p<0.009$).

Spatial features of the locus coeruleus functional gradient are associated with behavioral measures

Regarding cognitive variables, the gradient explained a significant amount of variance above the effects of age, sex and education in emotional memory scores - more specifically recollection of stimulus valence ($F = 2.632$, adjusted partial $R^2 = 0.224$, $p = 0.016$), recognition of previously seen objects associated with emotionally charged stimuli ($F = 7.992$, adjusted partial $R^2 = 0.552$, $p < 0.001$), priming ($F = 2.198$, adjusted partial $R^2 = 0.175$, $p = 0.042$), emotional reactivity to negative events ($F = 4.008$, adjusted partial $R^2 = 0.365$, $p < 0.001$) and reappraisal of emotional valence for negative stimuli ($F = 2.827$, adjusted partial $R^2 = 0.259$, $p = 0.012$) after FDR corrections. For a depiction of gradient spatial layouts associated with behavioral scores, see [Figure 3](#). Besides the overall spatial features, some of these tests were also associated with specific parameters of the spatial model, indicating a spatial gradient phenotype that is associated with lower scores of emotional memory and emotion regulation regardless of age, sex or education (see Supplementary Material, [Figure S1](#) for partial Spearman's rank correlation coefficients and statistical significance). In general, an old-like functional gradient exhibiting a loss of rostral-like connectivity and more clustered functional organization was associated with worse performance in emotional memory and emotion regulation tasks related to negative events. Overall spatial

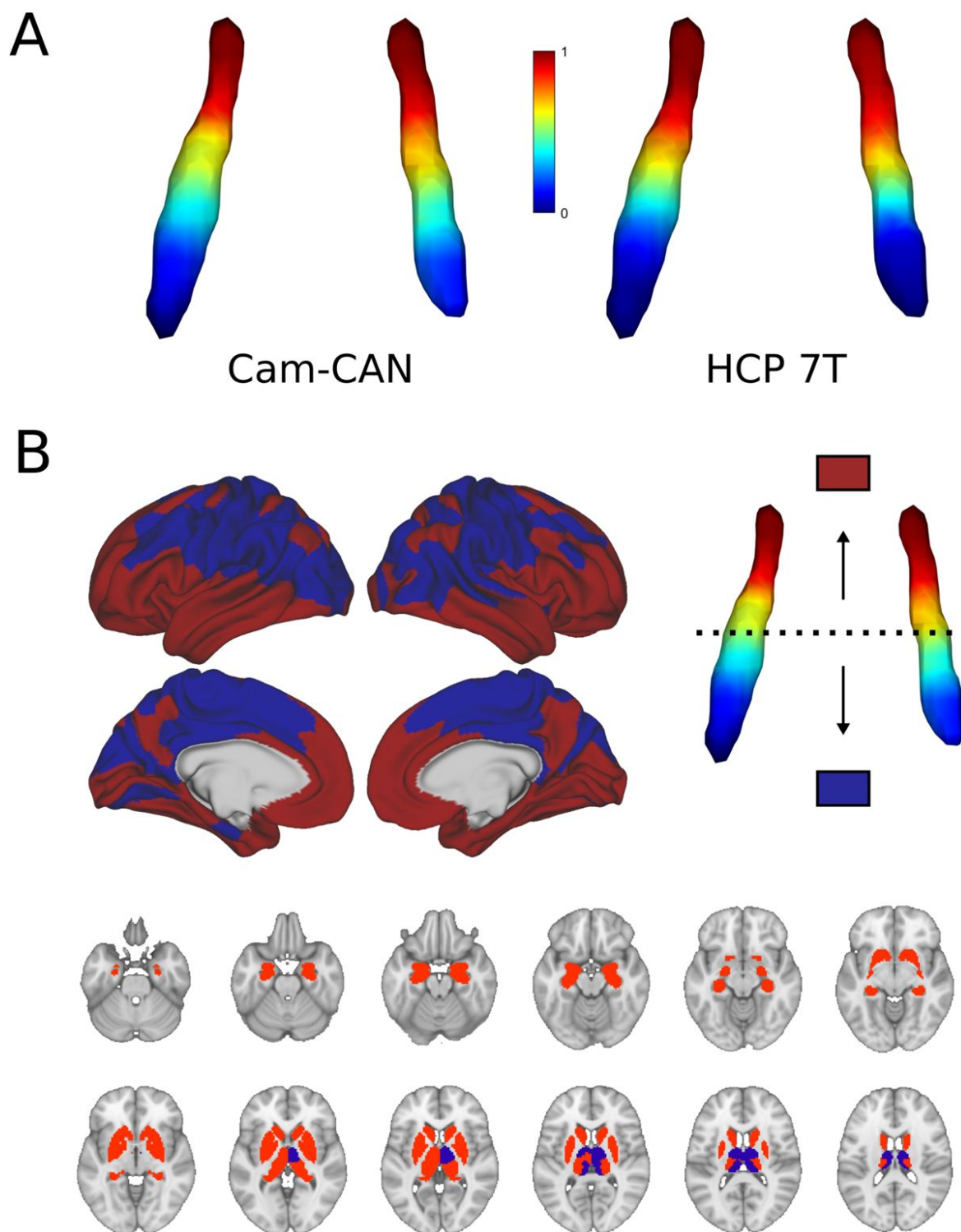


Figure 1.

Average functional gradients of the locus coeruleus in the Cam-CAN 3T and HCP 7T datasets.

A) Average functional gradients from subjects below 40 years of age in the Cam-CAN and HCP 7T datasets were projected to a surface rendering of the LC ROI mask. We present younger participants from the Cam-CAN cohort to make it comparable to the demographic characteristics of the HCP cohort. The color bar denotes normalized values of the dominant eigenmap. **B)** Projection maps of the LC were calculated as the mode of maximal correlation localization to either the rostral (red) or the caudal (blue) part of the LC in order to show the two extremes of connectivity. Projection maps were overlaid on the average HCP cortical surface and MNI152 template for the subcortical structures.

	Cam-CAN (n=618)	HCP 7T (n=184)
<i>Age range (years)</i>	18-88	22-36
<i>Biological sex (M/F)</i>	305/313	72/112
<i>Education years</i>	14.56 (4.02)	-
<i>Emotional memory – recollection</i>	1.58 (0.69)	-
<i>Emotional memory – recognition)</i>	2.63 (0.55)	-
<i>Emotional memory – priming</i>	0.41 (0.09)	-
<i>Emotion regulation – reactivity</i>	5.29 (1.63)	-
<i>Emotion regulation – reappraisal</i>	0.038 (1.11)	-
<i>Hotel-task</i>	301.93 (172.36)	-
<i>PSQI score (median, range)</i>	4 (0-22)	-
<i>HADS score (median, range))</i>	5 (0-20)	-

Table 1.

Demographic features of the Cam-CAN and HCP 7T cohorts.

Values in the table represent means followed by (standard deviations), except when stated otherwise. Measures from the emotional memory task represent d prime scores, which demonstrate the sensitivity of an individual to detect or correctly categorize stimuli in the given condition. Emotion regulation measures represent rescaled Likert-scale ratings, whereas the Hotel-task is scored as the average time in seconds a participant spends on each subtask. PSQI is a self-reported measure of sleep quality. HADS is a screening tool for anxiety and depression symptoms. Abbreviations: SD = standard deviation, M=male, F=female, PSQI=Pittsburgh Sleep Quality Index, HADS=Hospital Anxiety and Depression Scale.

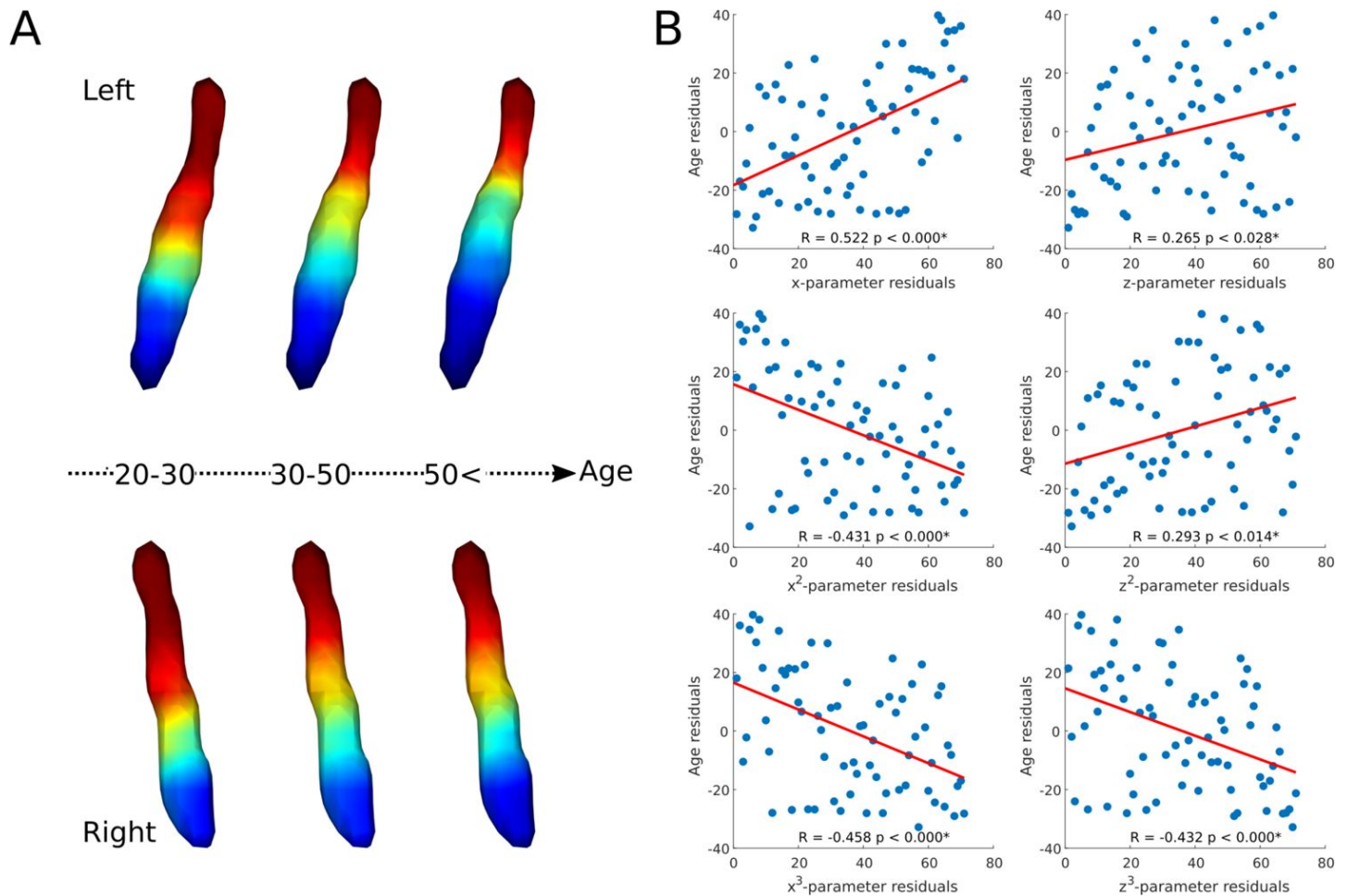


Figure 2.

Age-related changes in the locus coeruleus functional gradient.

Average functional gradients from representative age groups (20-30, 30-50, 50<) were projected to a surface rendering of the left and right LC ROI mask (**A**). The scatter plots show the relationship between age and rank-transformed values of TSM parameters (after adjusting for effects of sex) describing the spatial features of the gradient (see Methods for more details) with a least-squares line in red (**B**). Parameter changes correspond to a loss of rostral-like connectivity, increased asymmetry and more clustered functional organization of the LC in older participants.

features of LC functional gradients did not explain a significant amount of additional variance in executive functions (Hotel-task; $F = 1.473$, adjusted partial $R^2 = 0.036$, $p < 0.168$) or sleep quality scores (PSQI; $F = 1.124$, adjusted partial $R^2 = 0.01$, $p < 0.352$).

The locus coeruleus functional gradient is different in people with higher anxiety and depression ratings

Participants with higher-than-normal HADS scores exhibited a different gradient compared to participants with normal HADS scores (one-way MANOVA: $p < 0.001$). The gradient in the pathological group showed generally less rostral-like connectivity and was more asymmetric (left LC - z : $p < 0.002$, z^3 : $p < 0.007$; right LC: x : $p < 0.001$, z : $p < 0.001$, x^3 : $p < 0.001$, z^3 : $p < 0.001$; see **Figure 4**), showing a further reduction of left rostral-like connectivity compared to the right one.

Discussion

In this study, we show that functional connectivity in the LC is organized along a rostro-caudal gradient. This functional gradient was reproduced in two independent cohorts, and was driven by differential connections to the medial temporal lobe, hippocampus, amygdalae, striatum, medial parietal cortex and anterior cingulate (from the rostral part) and the visual, sensorimotor cortices and thalamus (from the caudal part). Importantly, we show that spatial variation and rostral-caudal balance showed age-related changes: specifically, a loss of rostral-like connectivity, a more clustered functional organization over the entire LC and an increased asymmetry were associated with older age. Moreover, these differences in the spatial characteristics of the LC gradient were associated with poorer emotional memory, emotion regulation, higher anxiety as well as depression scores, independently of age, sex and education. These findings highlight the essential role played by the LC in regulating memory, emotion and psychiatric symptoms through its heterogeneous patterns of functional connections projecting to different cortical and subcortical brain areas.

A rostral-caudal division has already been reported in the LC by studies using structural imaging and LC-contrast MRI sequences (39). This division seems to be driven by a heterogeneous distribution of cellular, molecular and connectivity-related characteristics along the LC. Specifically, LC-contrast MRI sequences such as magnetization transfer imaging seem to be associated with neuronal integrity in the LC, although the biological sources of this contrast are still not fully understood (40). A post-mortem study showed that noradrenergic neural somas in the LC show a specific distribution characterized by a dense collection of cell bodies in the central LC that disperses in both caudal and rostral directions, with a lower number of these noradrenergic cells in the caudal part compared to the rostral part (41). Using a gradient-based approach applied to functional imaging, we reproduced this structural division, revealing for the first time a rostro-caudal functional organization consistent across cohorts with different acquisition parameters.

In addition to distinct cellular distributions, spatial heterogeneity in the LC is also driven by projections to different brain areas along its longitudinal axis. Tracer studies show that the rostral-dorsal part of the LC projects to neocortical regions, the hippocampus, medial temporal lobe and amygdala, whereas the caudal-ventral part sends its main efferent projections to the cerebellum and medulla (42). Here we provide an *in vivo* account of LC functional projections, revealing that the connections most reproducible across cohorts, mainly from the rostral part, are in reasonable agreement with anatomical connectivity studies, and these connections drive the gradient of functional connectivity throughout the LC. However, in addition to tracer studies, we found that the caudal part also shows connectivity to primary sensorimotor and visual cortical regions, as well as the thalami. Some of these regions, especially the thalami, were reported to

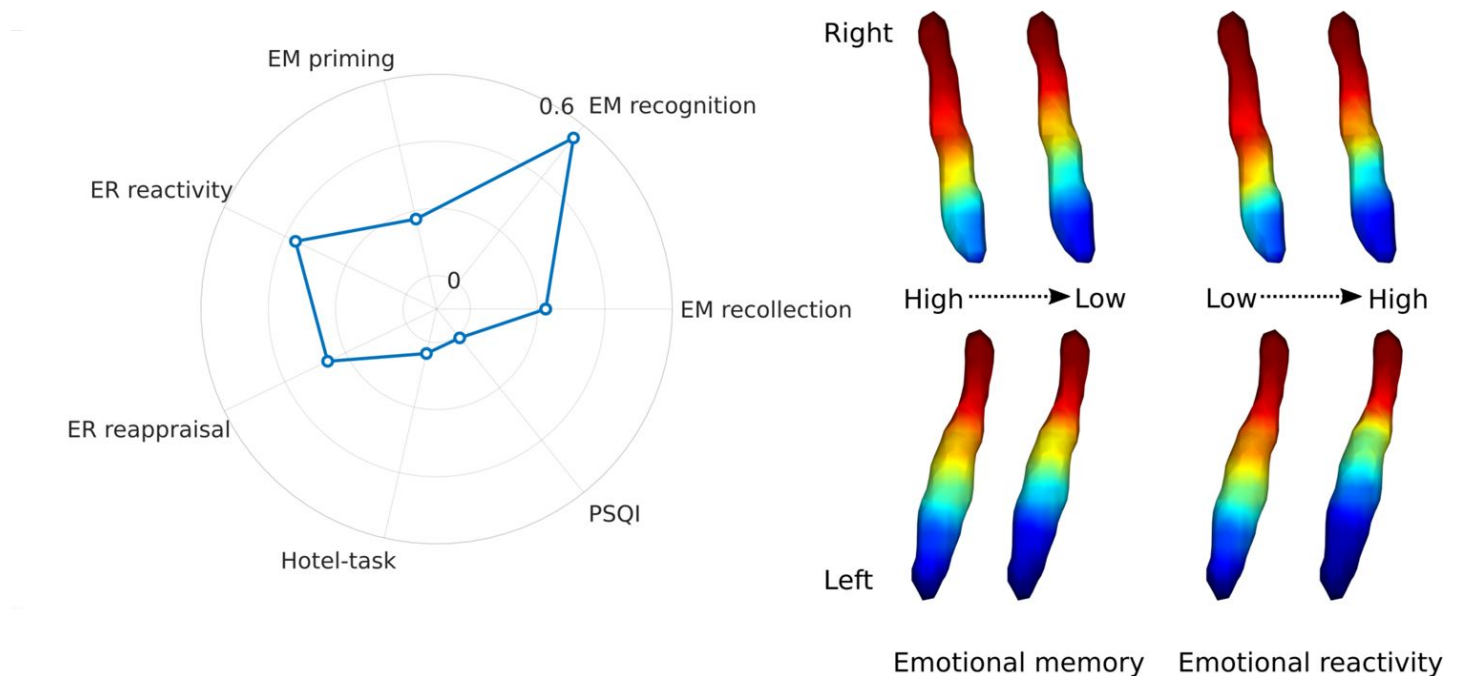


Figure 3.

Association of LC functional gradient spatial features and behavioral measures.

The polar plot depicts additional variance explained by spatial features of the LC functional gradient over and above nuisance variables (age, sex, education for the analyses to predict cognitive variables) in emotional memory, emotion regulation, executive function and sleep quality in terms of adjusted partial R^2 values. Example window-averaged gradients from participants with lowest and highest emotional memory scores and emotion regulation scores were projected to a surface rendering of the LC ROI mask, showing that old-like functional gradient spatial features (less extensive rostral-like connectivity and more clustered functional organization) are associated with lower scores in emotional memory and emotion regulation related to stimuli with negative valence. No significant associations were found with executive function and sleep quality. Abbreviations: EM=emotional memory, ER=emotion regulation, PSQI=Pittsburgh Sleep Quality Index.

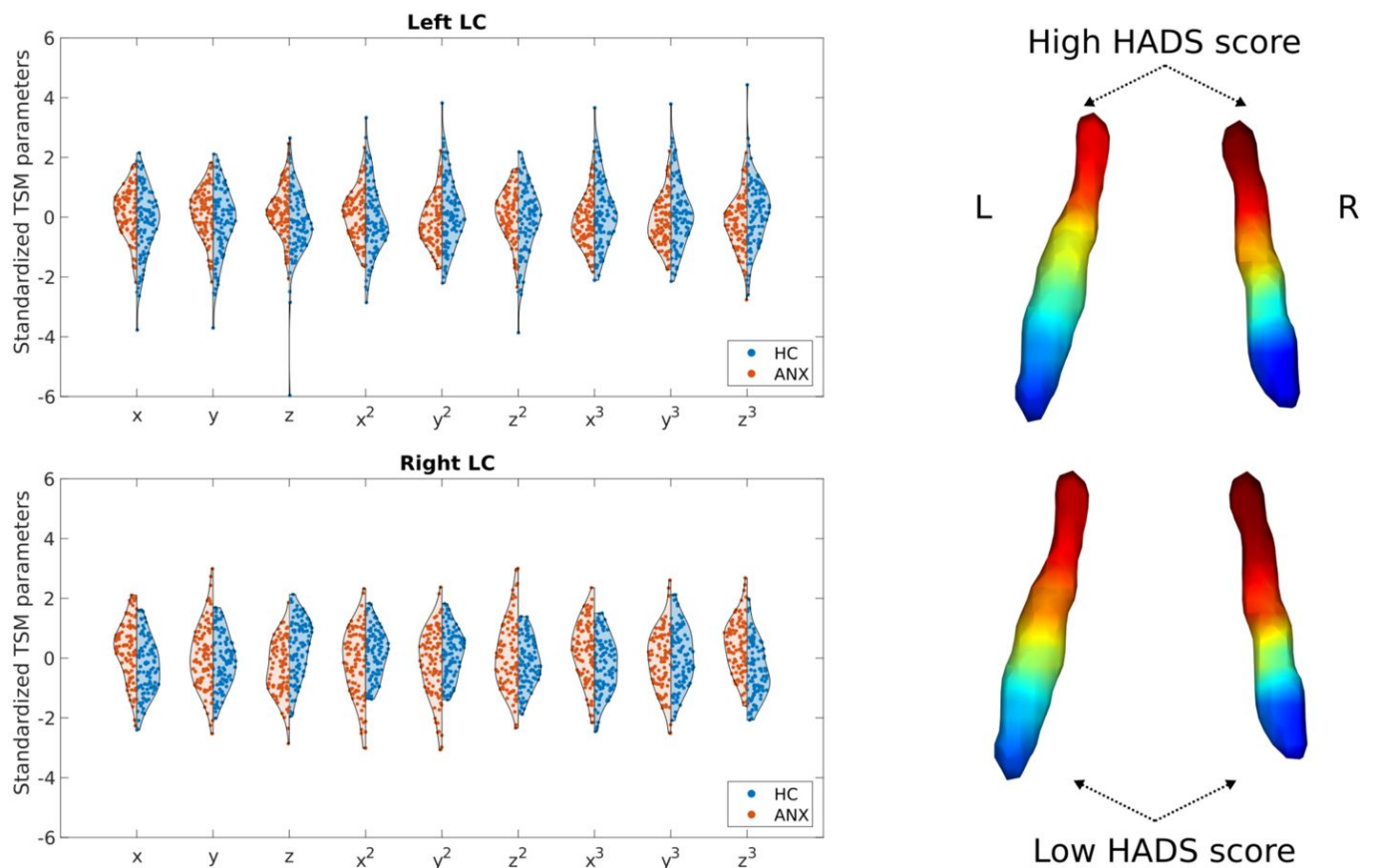


Figure 4.

Alterations of the LC functional gradient in participants with abnormal HADS scores.

The violin plots depict gradient spatial model parameter distributions in the two groups. Example gradients from participants with low and high HADS scores were projected to a surface rendering of the LC ROI mask, showing that high HADS scores were associated with a reduction of rostral-like connectivity, as well as a greater asymmetry in the spatial layout of the bilateral LC gradients.

show connectivity with the LC in previous fMRI studies (16). Regarding primary sensorimotor and visual regions, it is possible that downstream multisynaptic connections in these regions reflect the cerebellar projections of the caudal LC, since the cerebellum is known to have strong reciprocal connections to multiple thalamic nuclei and primary sensorimotor cortical areas (43). It is important to note that the fMRI acquisition in the CamCAN cohort did not cover the entire cerebellum and upper cervical spinal cord, which are known targets of projections in the caudal LC, therefore we did not investigate them in this study.

Since in vivo investigation of the LC is hindered by its small size and location, the functional implications of the heterogeneous structure and connectivity of the LC have not been fully explored. Electrophysiological studies report non-overlapping spontaneous activation dynamics from different sites in the LC that associate with and drive different cortical states, suggesting the presence of distinct neural ensembles in the LC that regulate multiple cortical states, instead of a homogeneous arousal-related release of noradrenaline across the cortex (44). Although fMRI provides a comprehensive view of LC function due to this nucleus' extensive and diffuse cortical projections, this technique is limited by low spatial resolution, which could explain why previous resting-state fMRI studies focused on the LC obtained inconsistent results (16,17). The high connectivity heterogeneity of the LC shown in our study indicates that using the LC as a single, homogeneous ROI might not be the best approach to assess connectivity in this region. We show that a gradient-based approach is able to uncover the functional organization of the LC, and that it is relevant to LC-related behavioral measures. Specifically, we found that the LC functional connectivity gradient shows age-related differences, and its spatial features correlated with several behavioral measures that were previously linked to the noradrenergic system. Functional connectivity of the LC has been demonstrated to depend on age, especially connections to the medial temporal lobe and amygdala projecting from the rostral part of this region (17). In line with this, we observed a loss of rostral-like connectivity with increasing age. Other in vivo MRI studies also reported that most age-related structural changes seem to be confined to the rostral part of the LC (15,45,46), and can be linked to age-related alterations in cortical thickness (47). These changes possibly stem from morphological alterations that affect neuromelanin-containing neurons in the rostral part, leading to a reduction in cell size and potentially cell loss, which might be associated with alterations in their projections as well (48). Another possible explanation is that, with advancing age, misfolded protein aggregates build up in the brain that may or may not cause manifest neurodegeneration later on (49). Recent research identified the LC as an early site for tau deposition, where accumulation of pathological proteins increases the risk for neurodegenerative conditions like Alzheimer's disease (50). Recent histological studies reported that the distribution of pathological proteins (especially tau neurofibrillary tangles) is non-uniform in the LC, preferentially affecting the rostral-dorsal part, irrespective of Braak stages (51). Early morphological changes in tau-containing LC neurons included gradual dendritic atrophy and changes in axonal morphology indicative of impaired axonal transport, which might contribute to earlier loss of connectivity in the rostral LC section during aging. Our results support these age-related effects on LC integrity and provide a functional imaging marker to assess accompanying regional changes in LC connectivity in vivo.

Independently of age, an old-like functional gradient was also associated with worse performance on emotional memory and emotion regulation scores, consistent with previous studies showing that lower rostral LC integrity is associated with worse memory performance in general (39). A possible explanation for this is the relationship between pathological amyloid- β buildup and decreased functional connectivity of the LC to the hippocampus and amygdala during the encoding of salient events (52). These connections were more characteristic of the rostral part of the LC in our study, where poorer memory performance was associated with a loss of rostral-like connectivity. Other studies further detail the association between LC integrity and memory, showing that the link between LC integrity and memory performance is more emphasized when participants try to recall aversive effects, which reflects the role of the noradrenergic system in the formation of emotionally charged memories (5). Furthermore, the LC functional gradient

was associated with emotion regulation, a process that is strongly associated with fear learning and development of anxiety, which have been linked to the noradrenergic system (53). The fact that the LC functional gradient reflected emotional memory performance and emotion regulation in our study independently of age points to the selectivity of the LC gradient in explaining these behavioral measures and its viability as a marker for emotional processing. Interestingly, we did not find an association between the LC functional gradient and executive functions or sleep quality. Although more detailed studies are needed, it is possible that the association between executive function and the LC is mostly mediated by age. Regarding the PSQI sleep quality indices, this questionnaire is a subjective assessment of sleep quality and more objective studies are needed to examine the effects of LC functional gradients on sleep architecture.

Furthermore, participants with higher anxiety and depression ratings exhibited a more asymmetric functional gradient, with the same parameters affected as in our results concerning aging. This is in line with previous studies reporting a role for the LC in the generation of anxiety and depression (54). The LC modulates stress-related arousal through its ascending norepinephrergic projections, and chronic stress involved in the pathogenesis of clinical anxiety amplifies tonic activity in the LC in response to subsequent stressors in animal models (55). Additionally, chronic stress is associated with differences in dendritic morphology in the prefrontal cortex of rats, which might impact efferent projections from the LC (56). Anxiety symptoms also seem to come with degenerative or maladaptive structural changes within the LC, since this condition was associated with morphological differences of the LC on ultra-high field MRI in animal (57) and human studies (58). Although the relevance of the LC in depression is mostly tied to its role in the development of anxiety and therefore stress-induced depression (59), there are several studies that report specific alterations of the LC in e.g. major depression disorder (MDD). A task fMRI study found decreased LC functional connectivity during a visual oddball task in patients with MDD (60). Apart from functional alterations, the LC also shows reduced structural integrity in patients with MDD (61), as well as molecular changes that manifest in lower levels of neuronal nitric oxide synthase, an intracellular mediator of glutamatergic signaling, in the LC (62). Regarding lateralized alterations of the LC functional gradient in participants with elevated anxiety and depression scores, asymmetry can be physiological to a point, since a lateralized signal distribution of the LC was observed in healthy adults in previous studies (45). Although future studies are needed to confirm this, it is possible that a more asymmetric LC functional gradient accompanying higher HADS scores reflects lateralized amygdala response alterations reported in previous studies of patients with anxiety disorders with accompanying plastic changes in LC connectivity (63). However, it is important to note that the HADS score represents a general assessment of a person's anxiety and depression levels, and more specific and detailed studies will be needed to elucidate how LC functional gradients are associated with anxiety and depressive symptoms.

Interestingly, we observed lateralized changes in the LC gradients both in connection with aging and cognitive performance. Generally, the LC connects to several highly lateralized cortical networks, e.g., the salience and frontoparietal attention networks, that might result in an asymmetric plasticity in the LC. Neurodegenerative disorders seem to affect the left LC more both in terms of integrity and connectivity. For example, more widespread loss of connectivity between the left LC and resting state networks was found in PD patients, with a correlation between left LC-executive control network connectivity and cognition (64). Another study found decreased connectivity between the left LC and the parahippocampal gyrus in mild cognitive impairment (65). Furthermore, increased left LC contrast was associated with aging and PD as well (4,45). However, the biological basis for this is elusive, as post-mortem studies generally find the bilateral LC symmetric and mostly report pathological changes in the rostral and middle LC (66). In our case, a possible interpretation is that with the loss of rostral-like connectivity, previously rostral-like areas lose their specific connections and become more similar to the caudal

part in terms of connectivity. In this study, since we did not investigate the cerebellum and the spinal cord, the typical caudal connectivity profile is more non-specific, since some of its dominant connections are not assessed.

This study has some limitations. Although we reproduced the functional gradients in a dataset with higher spatial resolution of 7T, the spatial resolution and coverage of 3T functional MRI scans is a limiting factor warranting further studies, as well as the fact that physiological data (such as pupil size tracking or respiratory monitoring) was not acquired during the 3T scans. A further technical limitation is that connectopic mapping requires a measure of spatial smoothness for gradient calculation, therefore we used a smoothing kernel of 3 mm FWHM and constrained it to the LC mask in order to avoid signal leakage. Also, the dataset used to investigate age-related changes is cross-sectional, and longitudinal studies need to be conducted in order to confirm the age-related differences we observed here. Because of the small ROI size and the limited temporal resolution of the 3T dataset, we employed a group-based approach to calculate the gradients, however, this limits the assessment of gradient reproducibility on the individual level, which should be explored in further studies. Furthermore, although the behavioral significance of functional gradients is increasingly recognized in correlational studies, further research is required to obtain more information about their underlying physiological role.

In conclusion, in this study we show that functional connectivity is organized into a gradient along the longitudinal axis of the LC. This functional gradient was reproducible across cohorts and different fMRI protocols, and showed relevant associations with age, memory, emotion, as well as anxiety and depression ratings. Therefore, our study provides an *in vivo* account of functional heterogeneity and organization in the LC, as well as a possible imaging marker for LC-related behavioral measures of memory and psychiatric symptoms.

Data Availability

The datasets supporting the conclusions of this article are available in the following repositories. Full imaging data from the Human Connectome Project is available at <https://db.humanconnectome.org>. Imaging and behavioral data from the Cam-CAN dataset is available at <https://www.cam-can.org>.

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Conflicts of interest

HZ has served at scientific advisory boards and/or as a consultant for Abbvie, Acumen, Alector, Alzinova, ALZPath, Annexon, Apellis, Artery Therapeutics, AZTherapies, CogRx, Denali, Eisai, Nervgen, Novo Nordisk, Optoceutics, Passage Bio, Pinteon Therapeutics, Prothena, Red Abbey Labs, reMYND, Roche, Samumed, Siemens Healthineers, Triplet Therapeutics, and Wave, has given lectures in symposia sponsored by Cellectricon, Fujirebio, Alzecure, Biogen, and Roche, and is a co-founder of Brain Biomarker Solutions in Gothenburg AB (BBS), which is a part of the GU Ventures Incubator Program (outside submitted work).

Supplementary material

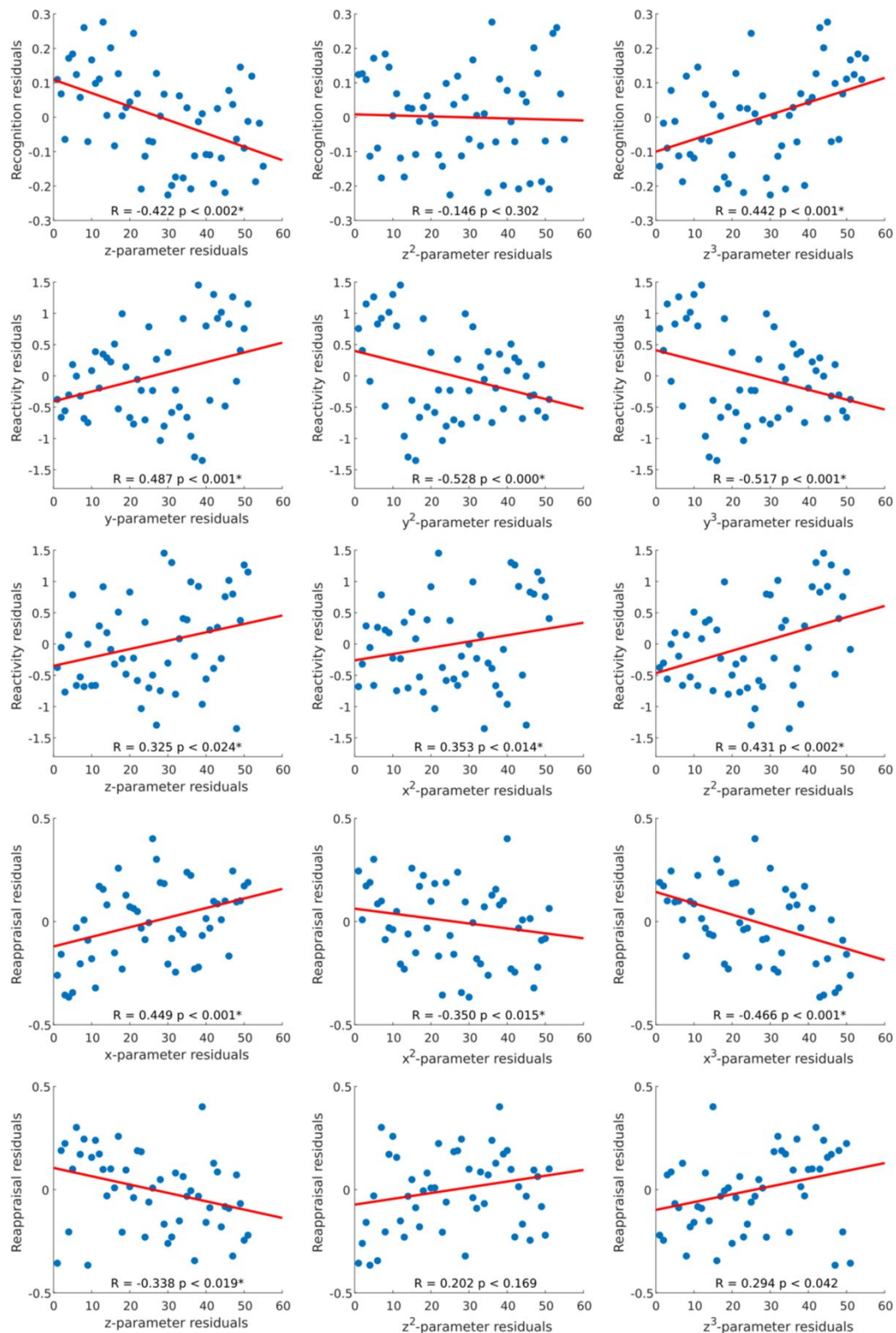


Figure S1.

Correlation plots of individual trend surface model parameters and cognitive scores.

The scatter plots depict residuals of rank-transformed gradient parameters and cognitive scores after correcting for age, sex and education, with a least squares line superimposed in red color.

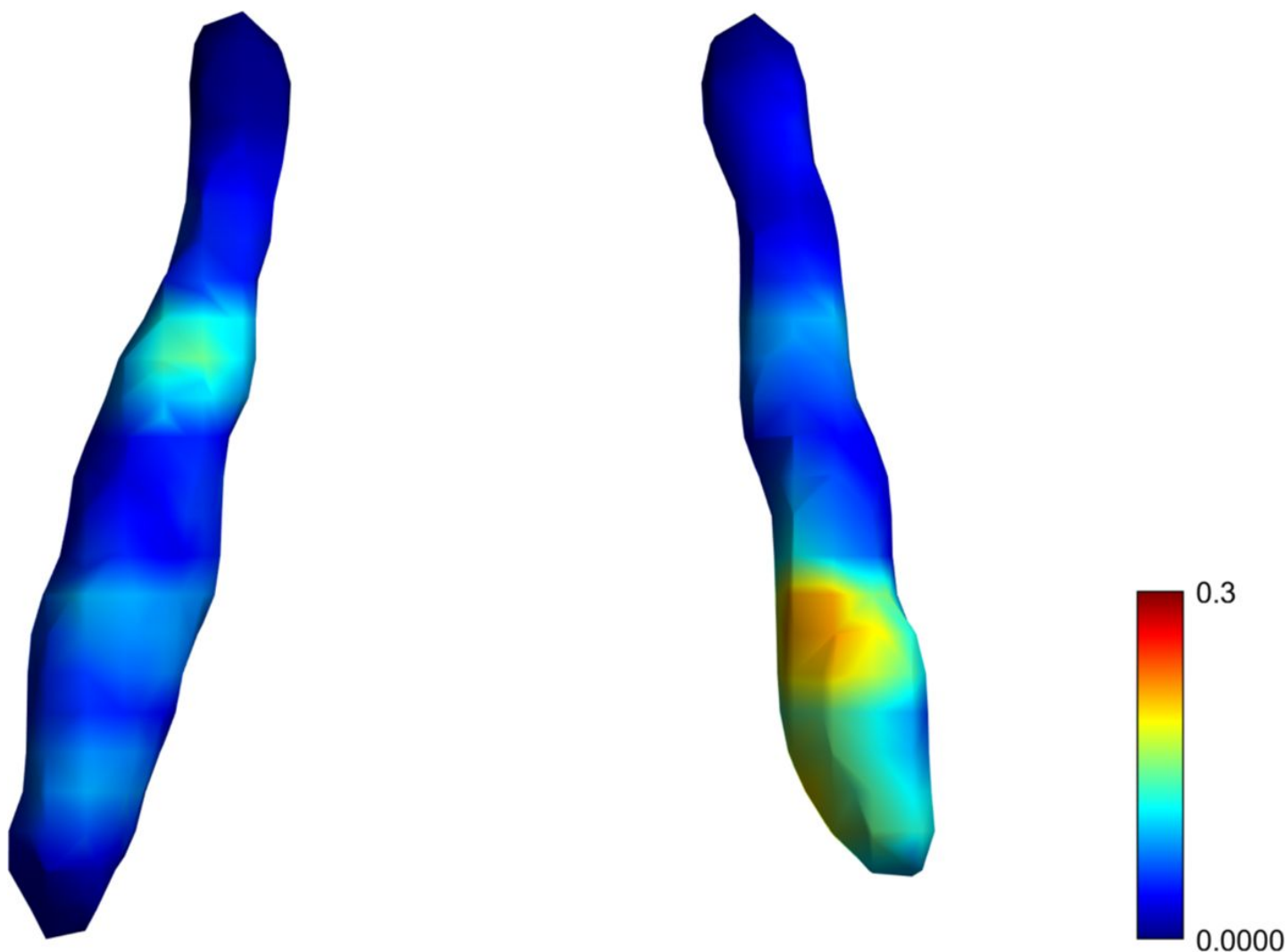


Figure S2.

Normalized difference map depicting the similarity of the gradient between subjects below 40 years of age from the CamCAN and the HCP 7T dataset.

We present younger participants from the Cam-CAN cohort to make it comparable to the demographic characteristics of the HCP cohort. The difference map was calculated as the absolute difference by subtracting the normalized CamCAN gradient from the normalized HCP gradient.

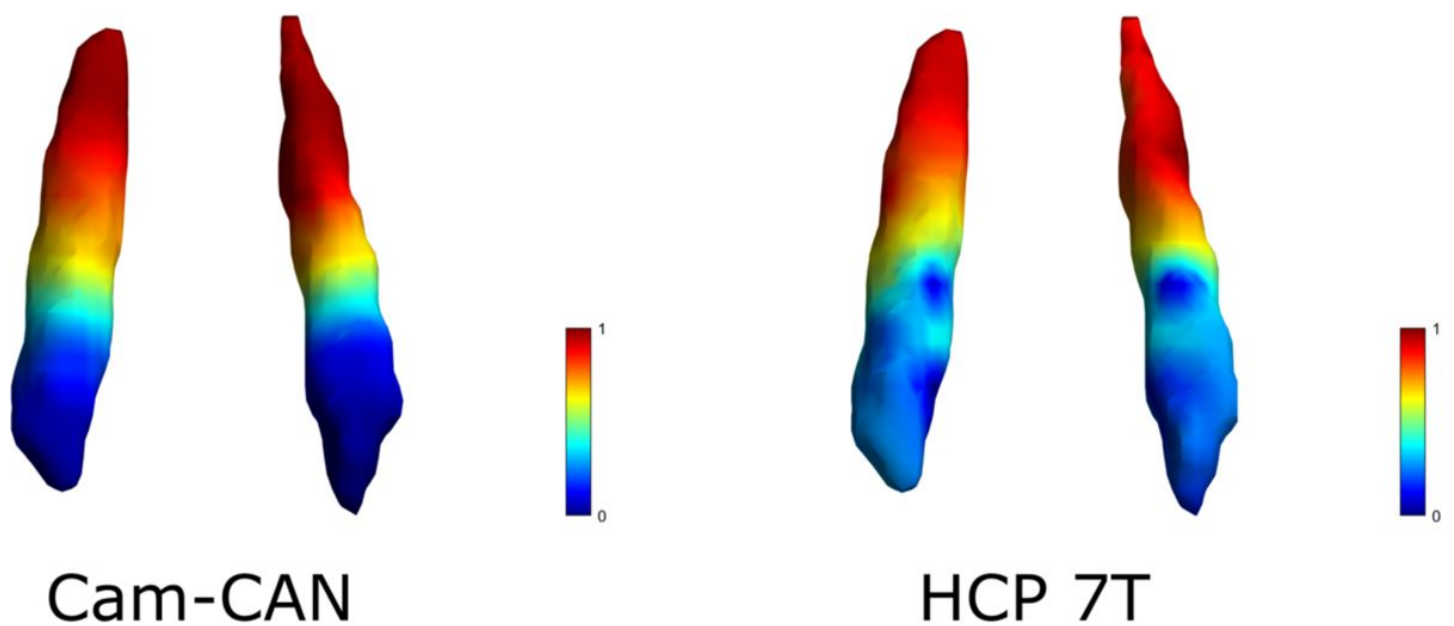


Figure S3.

Average functional gradients of the locus coeruleus in the Cam-CAN 3T and HCP 7T datasets using a LC ROI different from the main analysis. Average functional gradients from subjects below 40 years of age in the Cam-CAN and HCP 7T datasets were projected to a surface rendering of the LC ROI mask. We present younger participants from the Cam-CAN cohort to make it comparable to the demographic characteristics of the HCP cohort. The color bar denotes normalized values of the dominant eigenmap.

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Reviewer #1 (Public Review):

This study provides valuable imaging evidence for the connectopic mapping of the locus coeruleus where a rostro-caudal gradient was linked to heterogeneous functional organisations of the structure. The functional gradient of the LC changes over ageing and reflects capacities of related brain functions. The gradient approach is well-established and solid results were obtained and validated using large 3T and 7T fMRI dataset. The work highlights the importance of using more specific spatial definition of the LC based on distinct connectivity patterns in future resting-state fMRI studies.

Reviewer #2 (Public Review):

The authors have provided evidence for a rostral-caudal organisation of locus coeruleus connectivity, which they show i) differs across the lifespan, ii) is associated with relevant cognitive and mood measures. They have taken a data-driven, gradient-based approach, which was applied in the CamCan dataset and then replicated in the HCP dataset. This is a useful contribution to the field as it comprehensively shows a rostral-caudal pattern of connectivity in vivo, which has mostly been supported by tracer studies to date.

The strengths of the study are the large sample sizes and replication across two cohorts. The connectomic mapping approach they have applied is very well suited to the question at hand, as it allows a continuous gradient of organisation to be identified.

Author Response

The following is the authors' response to the original reviews.

Reviewer #1 (Public Review):

Comment 1. The authors used a meta-mask based on previous LC structural studies to delineate the LC on functional scans within two large public datasets (3T CamCAN and 7T HCP).

The rostral part of the LC was characterized by connections to the posterior and anterior cingulate cortices, medial temporal lobe, hippocampus, amygdala and striatum, while the caudal part projected to the parietal cortex, occipital cortex, precentral and postcentral regions, and thalamus. Older ages were associated with less rostral-like connectivity and increased asymmetry. The gradient explained variance above the effects

of age, sex and education on some emotional and cognitive measures. In particular, the old-like functional gradient (loss of rostral-like connectivity and more clustered functional organization) was associated with worse performance on emotional memory and emotion regulation tasks but not to executive functioning or self-rated sleep quality.

Participants with higher anxiety and depression also showed less rostral-like connectivity and more asymmetry. Both the aging and the anxiety/depression asymmetry manifested as less rostral-like connectivity in the left LC than the right LC.

A strength of this study is that it is the first to attempt a voxel-based approach to quantifying functional connectivity in the LC. The results finding differences between rostral and caudal LC connectivity patterns are broadly consistent with prior work indicating differences between rostral/caudal LC and should help advance understanding of the LC's connectivity patterns with cortical regions.

We thank the reviewer for the thorough and positive assessment of our manuscript.

Comment 2. A limitation of the study is the challenge of assessing activity not only from the small LC brainstem nucleus but also within it. Given the current spatial limitations of whole-brain functional imaging, the current findings are bolstered by including the 7T 1.6mm isotropic data. Spatial smoothing was applied with a 3mm FWHM isotropic kernel which may have reduced precision.

The reviewer raises valid points. Spatial resolution is indeed a limiting factor for assessing the LC with functional MRI. The choice of including spatial smoothing in the preprocessing was necessary because connectopic mapping requires a measure of spatial smoothness for the gradient calculation (see Haak et al. 2018 NeuroImage). We included a sentence explaining this in the revised version of the manuscript and added it also as an additional limitation.

Comment 3. Another limitation was that the authors made conclusions about clustered functional organization but it was not clear how clustering was quantified.

We thank the reviewer for the comment. Clusterability was quantified in the following way (based on Ngo et al. 2021 NeuroImage). First, gradient maps were clustered into $k=2$ clusters using the k-means clustering algorithm and then the Calinski-Harabasz criterion was calculated for each individual gradient map, which was used as a measure of clusterability. Higher criterion values were significantly associated with older age (Spearman's $\rho = 0.3129$, $p < 0.0089$), indicating that the gradient was more clustered in older individuals. This new analysis is now included in the revised version of the manuscript.

Reviewer #1 (Recommendations For The Authors):

Comment 1. Would it be equally accurate to state that participants with higher anxiety and depression showed more caudal-like connectivity or are the differences clearly localized to the rostral LC?

We thank the reviewer for the question. Since the gradients are by default a dimensionless scale that was further normalized to the range of 0-1, both interpretations are possible. We hypothesized a loss of rostral-like LC connectivity based on previous literature.

Comment 2. These resting-state findings seem to show some interesting parallels to the structural rostral/caudal LC MRI contrast relationships with cortical thickness in Bachman et al. (2021, Neurobiology of Aging), who found that positive associations between LC contrast and structural thickness were found among older adults for rostral

but not caudal LC (corresponding with the rostral regions showing the most age-related change). It is also interesting that in Bachman et al., younger adults showed negative correlations between caudal LC contrast and cortical thickness, which may relate to associations with a more caudal-like connectivity pattern (assuming this is a fair way to interpret the current results) in those with high HADS scores (i.e., rostral LC indicators may reflect stress/anxiety).

We thank the reviewer for pointing out these interesting findings. We included the reference in the revised version of the manuscript.

Comment 3. How was "more clustered functional organization" computed? I could not find description of this in the analysis section. If it is something that is evident from the visual depiction of the surface rendering shown in Fig. 2, please explain as it was not clear to me.

We thank the reviewer for the comment. As mentioned in a previous answer to a comment made by the Reviewer, clusterability was quantified in the following way (based on Ngo et al. 2021 NeuroImage). Gradient maps were clustered into $k=2$ clusters using the k-means clustering algorithm, then the Calinski-Harabasz criterion was calculated for each individual gradient map, which was then used as a measure of clusterability. Higher criterion values were significantly associated with older age (Spearman's $\rho = 0.3129$, $p < 0.0089$), indicating that the gradient was more clustered in older individuals. This analysis is now included in the revised version of the manuscript.

Comment 4. In the connectopic mapping methods, it is stated that the analysis starts by calculating functional connectivity matrices between all voxel time series in an ROI and time series from a target mask. That statement sounds as though there would be one time series from the overall target mask. It is then stated that the target mask consistent of brain areas from a cortical and subcortical parcellation. But it is not clarified if (as I assume was the case) time series were extracted for each parcel within the mask (and how many parcels there were - 180?).

We thank the reviewer for the helpful comment. Regarding the target mask, average time series were extracted from each parcel in the atlases separately, and then pairwise correlations were calculated with timeseries from all voxels in the ROI (the LC). We used the Glasser-atlas (which contains 360 parcels) as a cortical parcellation and the Tian-atlas (which contains 50 parcels) as a subcortical parcellation. The corresponding section of the manuscript now includes this clarification.

Comment 5. Then it is stated that "Afterwards, we obtained a similarity matrix from the functional connectivity matrices of LC ROI voxels by calculating the eta-squared measure." It would help here to explain a little more to clarify which things are being compared for similarity. Specifically, for which pairs was the eta-squared measure computed for?

The eta-squared measure was calculated between the functional connectivity profiles (or "fingerprints") for all pairs of voxels in the LC ROI. More specifically, one such fingerprint contains the Pearson correlation coefficients between a given LC voxel time series and the regional time series from the target mask. The similarity matrix contains the eta-squared similarity of these fingerprints, therefore one index in the similarity matrix contains the similarity between the fingerprints of two specific LC voxels. The corresponding section of the manuscript now includes this clarification.

Comment 6. In Fig. 3, I found the labeling of surface renderings confusing (i.e., did high->low apply to both rows? What about 'emotional memory'? do the top and bottom row correspond with the R/L LC?).

We thank the reviewer for the helpful comment and made some changes to Fig. 3 to clarify the labels. The upper row shows the right LC, whereas the bottom row shows the left LC. High->low and low->high applies to both rows. Regarding emotional memory, a worse performance on this task resulted in lower scores. With emotional reactivity, higher scores indicate a worse ability to regulate negative ratings on the task, which results in an inverse relationship of this score with the LC gradient features. We also extended the figure label to include this explanation.

Response to Reviewer #2 (Public Review):

Comment 1. One of the major strengths in the current study is the implementation of the fully data-driven, gradient-based method for mapping connectopies of the LC. This approach is especially suited for brain structures that are difficult to localise because the resulted connectopic mapping is relatively robust to ROI definition (Fig. 7 in Haak et al., 2018). However, as a very inclusive definition of the LC (the "meta atlas") was adopted in the study, to what extent the gradient approach can tolerate changes of accuracy and specificity for LC ROI definition is unknown. Some comparative analyses would be helpful to provide assessments on the specificity and stability of the reported gradient pattern.

We thank the reviewer for the positive assessment of our manuscript. Indeed, an advantage of the connectopic mapping approach is that it is less sensitive to minor ROI inaccuracies, which is convenient for the LC. We repeated the gradient calculation using a larger LC mask from Tona et al. (2017), and included a supplementary figure (Figure S3) that shows how the gradients still retain their rostrocaudal pattern using both LC masks.

Comment 2. Haak et al. showed distinct reproducibility within and between subjects when comparing connectopic mappings between M1 and V1. M1 connectopic mapping showed very high consistency across subjects (ICCs > 0.9) compared with V1. This is very reasonable because the functional organisation within M1 is relatively homogeneous. Regarding the reliability of the LC rostro-caudal gradient, the authors only stated that "individual gradient estimation is often not consistent", but direct measurement on the consistency across subjects for the LC gradient was missing. This is important for future LC fMRI studies as more consistent pattern might warrant the application of an atlas-based method otherwise a more individualized pipeline is needed for investigating functional dissociation in LC subregions.

We thank the reviewer for the question. Indeed, investigating the replicability of gradients at the individual level is important. However, regarding the LC, because of the ROI size and the relative shortness of the scans in the Cam-CAN dataset, we did not calculate individual level gradients and resorted to a group-level approach as we described in the method. Therefore, the assessment of individual reliability was outside of the scope of the current study. We included this as a limitation in the Discussion of the revised manuscript.

Comment 3. It puzzles me that why a dichotomous rostral vs caudal comparison was used to demonstrate the difference in connectivity patterns along the rostro-caudal gradient which might be an oversimplistic approach as described by the authors themselves? In fact, it might be more interesting to include the central "core" LC which is structurally organized in high density (Fernandes et al., 2012) and functionally distinguishable to the peri-LC "shell" region (Totah et al., 2018; Poe et al., 2022).

We thank the reviewer for the comment. Indeed, during the analyses we tried to delineate a central core region within the LC, however, the functional connections in this region varied greatly between individuals and we failed to reliably detect a functionally distinct central core region using FC. One reason for this might unfortunately be the limited spatial resolution of functional MRI. Instead, we hypothesized that the gradient manifests in fMRI connectivity of the LC by a gradual transition of connectivity profiles between the two dominant extremes of the caudal and rostral LC and we aimed to depict these two extremes in Figure 1. Although it is a simpler approach compared to the results of histological studies, we demonstrate in the paper that it still provides valuable information about LC in aging and LC-related behavioral measures.

Comment 4. The composition of rostral vs caudal connectivity pattern changes over ageing, where the loss of rostral-like connectivity was consistent in bilateral LC whereas the gain of caudal-like connectivity in older subjects was only evident in the left LC. Do authors have any explanations on this left-lateralised ageing effect which is interestingly coincided with a lot of observations such as increased left LC contrast ratios was found during ageing (Betts et al., 2017) and in PD patients (Ye et al., 2022), reduced left LC-parahippocampal gyrus connectivity was reported in aMCI patients (Jacobs et al., 2015).

We thank the reviewer for the question. Indeed, we observed lateralized changes in the LC gradients both in connection with aging and cognitive performance. Generally, the LC connects to several highly lateralized cortical networks, e.g. the salience and frontoparietal networks, which might result in an asymmetric plasticity in the LC. Interestingly, neurodegenerative disorders seem to affect the left LC more, e.g. more widespread loss of connectivity between the left LC and resting state networks was found in PD patients, with a correlation between left LC-executive control network connectivity and cognition (Sun et al. 2023). However, the biological basis for this is elusive, as post-mortem studies generally find the bilateral LC symmetric and mostly report pathological changes in the rostral and middle LC (Beardmore et al. 2021). In our case, a possible interpretation is that with the loss of rostral-like connectivity or previously rostral-like areas lose their specific connections and become more similar to the caudal part in terms of connectivity. In our study, since we did not investigate the cerebellum and the spinal cord, the typical caudal connectivity profile is more non-specific, since some of its dominant connections are not assessed. This interpretation is now included in the revised version of the manuscript.

Reviewer #2 (Recommendations For The Authors):

Comment 1. Minor:

- the preprocessing pipeline for HCP 7T data was not reported.

We extended the details of the preprocessing pipeline for the HCP 7T dataset.

Comment 2. - a difference map would be useful to demonstrate the similarity of LC connectivity gradient between CamCAN and HCP dataset.

We have now added a difference map between the CamCAN and HCP gradient in the supplementary material (Figure S2).

Comment 3. - labels for left and right LC were missing in Fig 3.

We corrected the labeling in Figure 3.

Comment 4. - in Statistical Analysis, CamCAN participants were divided into two groups with and without depressive and anxiety symptoms. It is unclear whether participants with high HADS scores were presented with both symptoms or just one of them.

Because of the low number of participants with high depression scores on the HADS test, we defined high HADS scores as individuals scoring above normal on either the anxiety part, the depression part, or both.