Multimodal brain age prediction using machine learning: combining structural MRI and 5-HT2AR PET derived features

Ruben Dörfel[1,2], Joan M. Arenas-Gomez[2], Claus Svarer[1], Melanie Ganz[2,3], Gitte M. Knudsen[2,4], Jonas E. Svensson[1,5], Pontus Plavén-Sigray[1,2]

1. Centre for Psychiatry Research, Department of Clinical Neuroscience, Karolinska Institutet, & Stockholm Health Care Services, Region Stockholm
2. Neurobiology Research Unit, Copenhagen University Hospital, Rigshospitalet, Copenhagen, DK
3. Department of Computer Science, University of Copenhagen, Copenhagen, DK
4. Department of Clinical Medicine, University of Copenhagen, Copenhagen, DK
5. Theme Inflammation and Aging, Karolinska University Hospital, Stockholm, Sweden.

Corresponding authors:

Pontus Plavén-Sigray, Email: pontus.plaven-sigray@ki.se

Abstract

To better assess the pathology of neurodegenerative disorders and to evaluate the efficacy of neuroprotective interventions, it is required to develop biomarkers that can accurately capture age-related biological changes in the human brain. Brain serotonin 2A receptors (5-HT2AR) show a particularly profound age-related decline and are also widely reduced in, e.g., Alzheimer's disease. Hence, cerebral 5-HT2AR binding measured in vivo using positron emission tomography (PET) is a potentially useful biomarker for age-related changes in the brain.

In this study, we investigate the decline in 5-HT2AR binding to evaluate its usefulness as a biomarker for biological aging. Specifically, we aim to 1) predict brain age using 5-HT2AR binding outcomes, 2) compare 5-HT2AR-based predictions of brain age to predictions based on gray matter (GM) volume, as determined with structural magnetic resonance imaging (MRI), and 3) investigate whether combining 5-HT2AR and GM volume data improves prediction. We used PET and MR images from 209 healthy individuals aged between 18 and 85 years (mean=38, std=18). 5-HT2AR binding and GM volume were calculated for 14 cortical and subcortical regions. Different machine learning algorithms were used to predict age based on 5-HT2AR binding, GM volume, and the combined measures. The mean absolute error (MAE) and a cross-validation approach were used for evaluation and model comparison.

We find that both the cerebral 5-HT2AR binding (mean MAE=6.63 years, std=0.78 years) and GM volume (mean MAE=7.76 years, std=0.92 years) predict chronological age accurately. Combining the two measures improves the prediction further (mean MAE=5.93 years, std=0.82). We conclude that when it comes to predicting age, in vivo measurements of the cerebral 5-HT2AR binding are more informative than GM volumes.

Introduction

Aging is associated with a wide range of molecular and cellular changes throughout an individual's lifespan, resulting in the deterioration of physical condition (Mattson and Arumugam, 2018; Moqri et al., 2023; Rose, 2009). Biological changes caused by aging are the main drivers for overall mortality and chronic pathology (Niccoli and Partridge, 2012). Pathological brain aging results in cognitive impairment (Sauver et al., 2015) and a predisposition to neurodegenerative disorders, such as Alzheimer's and Parkinson's disease (Hou et al., 2019). To describe the degree of pathology in neurodegenerative disorders and to assess the effects of eventual interventions meant to remediate the effect of biological aging, it is required to have access to biomarkers that can robustly capture such changes (Higgins-Chen et al., 2021; Moqri et al., 2023).

By using large neuroimaging datasets covering the human lifespan, it is possible to study changes in aging-related brain biology noninvasively. Using structural magnetic resonance imaging (MRI), a robust age-related decline in the volume of gray matter (GM) and white matter with different rates of decline over the lifespan has been shown (Bethlehem et al., 2022). Most work so far has been done using structural MRI, where large datasets are publicly available. Other neuroimaging modalities have also been used to study the effects of aging on the brain. Functional MRI data supports a decline in functional connectivity (Nielsen et al., 2019), and diffusion-weighted MRI studies have linked demyelination and axonal degeneration to increasing age (Cox et al., 2016). Positron emission tomography (PET) allows for in vivo quantification of proteins and processes that change with increasing age, such as metabolism, neuroinflammation, and many neurotransmitter systems (Bäckman et al., 2011; Karrer et al., 2019; Schuitemaker et al., 2012).

A common observation in a range of PET tracers is an association between radioligand binding and age (Varnäs et al., 2004; Wong et al., 1984). One receptor type that shows a particularly strong age-related decline in PET studies is the serotonin 2A receptor (5-HT2AR) (Adams et al., 2004; Frokjaer et al., 2009; Karrer et al., 2019; Moses-Kolko et al., 2011; Rosier et al., 1996; Sheline et al., 2002; Talbot et al., 2012). In the human brain, 5-

HT2ARs are mainly located in the neocortex layer V and, to a lesser degree in subcortical regions such as the hippocampus and putamen (Varnäs et al., 2004). The 5-HT2AR is reduced in a number of neurodegenerative diseases, such as Alzheimer's disease (Hasselbalch et al., 2008; Leysen, 2004; Versijpt et al., 2003).

Machine learning (ML) allows for modeling the healthy aging brain by summarizing aging brain biology from neuroimages into one single variable, called "*brain age*"(Cole et al., 2017; Franke et al., 2010). Models are trained to predict chronological age on imaging data from healthy individuals based on structural or functional change that occur over the human lifespan. The result is a model of a healthy aging brain, indicating how an average healthy brain would change during an individual's lifespan. More than the predicted age itself, the deviation of the predicted age from the true chronological is of interest. This deviation is hypothesized to reflect divergence from the expected healthy aging trajectory (J. H. Cole et al., 2018). The deviation between predicted age ($\hat{A}$) and chronological age (A) is expressed as the predicted age deviation (PAD):

$$PAD = \hat{A} - A. (1)$$

Under this hypothesis, a higher predicted than chronological age reflects a biologically older brain. Following from this, a positive PAD should translate to an increased risk for aging-related disorders. An increased PAD has been linked to increased cardiovascular risk (Wagen et al., 2022), overall mortality (J. H. Cole et al., 2018), neurodegenerative disorders, and cognitive decline (Bashyam et al., 2020; Gaser et al., 2013; Han et al., 2021; Kaufmann et al., 2019; Liem et al., 2017).

Here we aim to investigate if the age-related decline in 5-HT2AR binding can be utilized in the brain age paradigm. Specifically, the first aim is to apply ML algorithms to 5-HT2AR binding outcomes from PET images to predict brain age. The second aim is to compare these estimates to those derived from applying the same algorithms to volumetric GM data derived from structural MR images. The third aim is to investigate whether a multimodal approach combining 5-HT2AR binding and GM measures improves the prediction of brain age.

Materials and Methods

Imaging Data

Dataset

The Center for Integrated Molecular Brain Imaging (Cimbi) database (Knudsen et al., 2016) stores a large collection of high-resolution 5-HT neuroimaging data from healthy individuals. Here we included healthy participants from the Cimbi database where 5-HT2AR PET and structural MRI data were available. In total 209 individuals were included in the study. For imaging, the two PET radioligands [^{11}C]Cimbi-36 (Ettrup et al., 2014) or [^{18}F]altanserin (Lemaire et al., 1991) were used. The demographics and PET acquisition details are summarized in Table 1.

PET and MRI image acquisition

The MRI scans were acquired on Siemens (Siemens, Erlangen, Germany) scanners with a field strength of either 1.5T or 3T using 3D magnetization-prepared rapid gradient-echo sequences. All [^{11}C]Cimbi-36 PET scans were acquired on a Siemens High-resolution Research Tomograph system (HRRT; CTI/Siemens, Knoxville, TN, USA), whereas all [^{18}F]altanserin scans were acquired on a GE-Advance scanner (GE, Milwaukee, WI, USA). [^{11}C]Cimbi-36 was administered as an intravenous bolus injection with data collected for two hours (Ettrup et al., 2014). [^{18}F]altanserin was administered intravenously, starting with a bolus injection followed by continuous infusion. Data acquisition started two hours after [^{18}F]altanserin injection to allow for a steady state to be reached and lasted for 40 minutes. For all [^{18}F]altanserin scans, a venous blood sample was obtained, and metabolite-corrected radioactivity was quantified to allow for the correction of radionuclide-labeled metabolites entering the brain (Pinborg et al., 2003).

Table 1: The demographics of the used subsets.

	Scans	Gender Male / Female	Age min/max	Age mean (std)	PET Camera GE / HRRT	MR Scanner 1.5T / 3T
[^{11}C]Cimbi-36	67	39 / 28	18.4 / 58.3	28.3 (7.7)	- / 67	- / 67
[^{18}F]altanserin	142	90 / 52	18.5 / 81.7	40.5 (18.5)	142 / -	70 / 72
Total	209	129 / 80	18.4 / 81.7	36.6 (16.8)	142 / 67	70 / 139

Image pre-processing

All PET images were corrected for inter-frame motion using the AIR algorithm (v5.3.0) (Woods et al., 1992). The MR images have been corrected for spatial distortions due to nonlinearities in gradient fields. This preprocessing was part of the Cimbi database curation.

Standard FreeSurfer (v7.2) segmentation and parcellation pipelines (Fischl, 2012) were applied to the MR images to retrieve masks for cortical and subcortical regions of interest (ROIs) from the Desikan-Killiany (Desikan et al., 2006), and Aseg atlas (Fischl et al., 2002). Cortical ROIs were grouped into seven larger cortical regions (frontal lobe, occipital lobe, parietal lobe, temporal lobe, parahippocampal gyrus, cingulate, and insula) (Klein and Tourville, 2012) with high 5-HT2AR binding, as identified by autoradiography (Pazos et al., 1987; Varnäs et al., 2004). Additionally, seven subcortical brain regions were used in the analysis (thalamus, caudate, putamen, pallidum, hippocampus, amygdala, and nucleus accumbens). All regions were averaged across hemispheres, resulting in 14 ROIs (Table S1). The MR images were co-registered to a summed PET image using SPM8. The resulting co-registration matrix was used to project the ROI masks on the dynamic PET files to extract time-activity curves (TACs) for each region.

Brain Age Modelling

Outcome Measures

The volume of all ROIs was extracted from the FreeSurfer output and normalized using the estimated total intracranial volume (Buckner et al., 2004). Regional binding potentials (BPs) were calculated using the regional TACs extracted from the PET data. The cerebellum excluding vermis was used as a reference region, as it has a negligible density of 5-HT2ARs (Ettrup et al., 2014). 5-HT2AR binding from [^{11}C]Cimbi-36 scans was quantified as the non-displaceable binding potential (BP_{ND}) using multilinear reference tissue model 2 (Ichise et al., 2003), with k2' being estimated using the simplified reference tissue model applied to a TAC extracted from a mask over the entire neocortex. Quantification of [^{18}F]altanserin binding has been described in detail elsewhere (Pinborg et al., 2003). In short, the ratio of specifically bound radioligand to that of total parent radioligand in plasma, (BP_P) was calculated and used as the outcome measure. Even though BP_P and BP_{ND} are different measures, both are proportional to the density of the 5-HT2AR and highly correlated (Ettrup et al., 2016).

Machine learning algorithms

To develop a model of healthy aging brain, a set of ML algorithms were trained to predict chronological age from imaging-derived GM volume and 5-HT2AR binding data. The algorithms were implemented using scikit-learn (v1.2) (Pedregosa et al., 2011) in python 3.9.12. We selected commonly used algorithms for brain age prediction (Baecker et al., 2021; J. Cole et al., 2018): 1) Bayesian Ridge Regression (BRidge), 2) Relevance Vector Regression (RVR) implemented using *ARDRegression*, 3) Gaussian Process Regression with linear kernel (linGPR) 4) Gaussian Process Regression with radial basis function kernel (rbfGPR), and 5) linear support vector regression (linSVR). The selected algorithms were trained on either 5-HT2AR binding outcomes, GM volumes, or both. The multimodal model, combining structural MRI and 5-HT2AR PET derived data, was implemented as a stacking regressor (Wolpert, 1992). In a stacking regressor, a base model for each modality was trained, with

outcomes then used as input into a linear regression model. The algorithms BRidge, RVR, linGPR, linSVR, and rbfGPR were used as a base estimator, resulting in five ensemble regressors.

Baseline predictors

Two references were implemented to put the results into perspective. First, we trained a dummy regressor that always outputs the mean age of the training. Second, we applied pyment, a pre-trained state-of-the-art structural MRI-based brain age prediction software. pyment uses a skull-stripped, and MNI-space registered T1w-image as input (Leonardsen et al., 2022). It was originally trained on images from 53542 healthy individuals and has been shown to predict age on unseen data with high accuracy and reliability (Dörfel et al., 2023).

Experiments

We predicted chronological age based on the three feature sets (5-HT2AR, GM, and 5-HT2AR + GM) as well as the two reference models. An overview of the respective prediction pipelines is presented in Figure 1. The different outcome measures for [^{11}C]Cimbi-36 and [^{18}F]altanserin were aligned by transforming regional 5-HT2AR BP_{ND} to BP_P-like values based on age-matched subsets using a distribution mapping approach (Properzi et al., 2019), described in the supplement (S1.2). Subsequently, the matched values were standardized (zero mean, unit variance). GM volumes were similarly z-scored. A multimodal brain age estimate was calculated combining 5-HT2AR binding and GM volume features using the stacking approach previously described. Each feature set was transformed as described before.

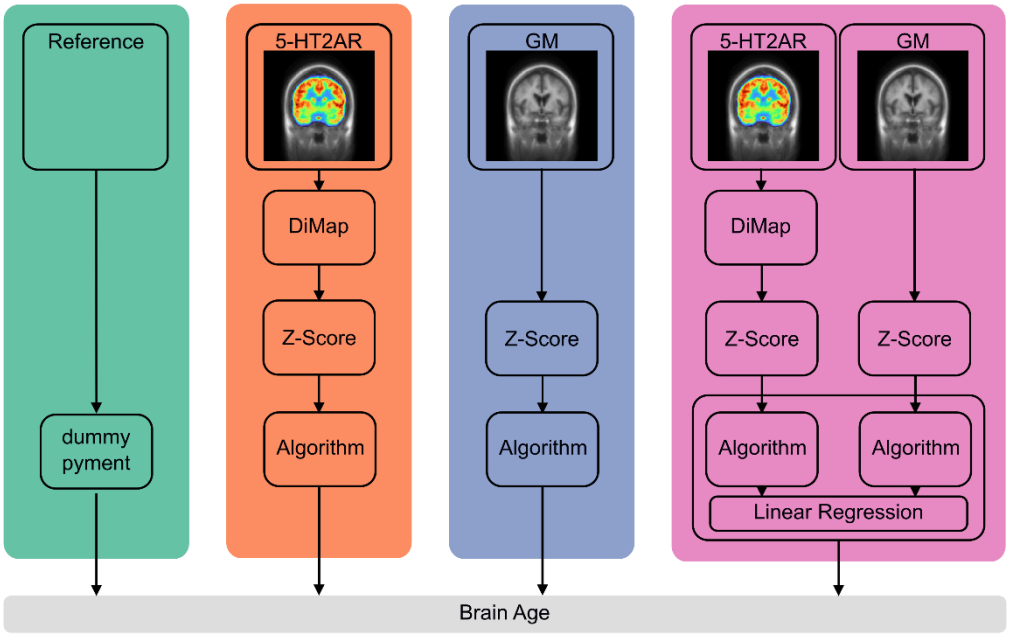

Figure 1: Overview of the prediction pipelines. **Reference:** the pre-trained MRI-based prediction model pyment and a dummy regressor always predicting the mean chronological age training data. **5-HT2AR:** BP_{ND} ([^{11}C]Cimbi-36) is transformed to BP_P-like units using the distribution mapping (DiMap). BPs are then z-scored. **GM:** Volumes of cortical and subcortical regions are z-scored. **5-HT2AR+GM:** Transformations for 5-HT2AR and GM features are identical to the unimodal counterparts. Brain age is predicted using a stacking ensemble method where a base model is trained for each modality, with the outcome used as input into a final estimator.

Model training and evaluation

Model accuracy was assessed using the mean absolute error (MAE), calculated as the average absolute difference between predicted and chronological age for each validation fold. The generalization error of each model was estimated based on the 100 hold-out folds in a 20-times repeated 5-fold cross validation (CV) setup (Varoquaux et al., 2017). An additional inner 5-fold CV was used for hyperparameter tuning, if necessary. The initial split was randomly shuffled for each of the 20 repetitions to gain a split-independent estimate of the generalization

error. The outer five-fold CV was stratified by age to ensure the same age distribution between the training and validation sets.

The generalization error for each model was then estimated as the average MAE over all folds (N=100)

$$E_{gen} = \frac{1}{N}\sum_{i}^{N} MAE_i \,. \qquad (2)$$

Further, Pearson's *r* was calculated between chronological and brain age. The correlation coefficient should be close to one, if the estimated brain age perfectly follows the chronological age in this population of healthy participants. Pearson's r was also calculated between chronological age and PAD (see eq. 1) values. Here, the correlation coefficient should be close to zero as the PAD is supposed to reflect deviations from the healthy aging trajectory and should not be associated with chronological age. The coefficient of determination (R^2) was calculated to assess how much variance in the predicted variable (chronological age) was explained by the respective model. To describe the strength of the association or explained variance, we used the following heuristic: an *r/R2* between 0–0.19 was described as negligible, 0.2–0.39 as weak, 0.40–0.59 as moderate, 0.6–0.79 as strong/large and 0.8–1 as very strong/large (Campbell, 2021).

Model Comparisons

To assess whether GM volumes are more predictive of age than 5-HT2AR binding in the same regions and whether a multimodal approach (combining 5-HT2AR+GM features) can improve predictions, we tested the best model trained on GM or 5-HT2AR+GM features against the best model trained on only 5-HT2AR features using a paired two-tailed t-test. Specifically, the MAE per fold for each model was used for comparison. As most of the training data overlaps in each CV split, the assumption of independence between the CV folds within each repetition was violated. Therefore, a correction to the t-test was applied to adjust for this dependence (Benavoli et al., 2017; Nadeau, 2003). The significance level was set to 0.05.

Modality contribution and feature importance

To investigate the similarity between predictions, we correlated predictions of the models based on GM volumes and 5-HT2AR binding. A high correlation coefficient would indicate that the information in both feature sets leads to similar brain age predictions. As an underlying strong correlation with chronological age is expected, we also correlated the PAD values from the different feature sets. Additionally, we investigated the weight for each modality in the stacking process of the combined model. This indicates which feature set contributes most to the final predictions of the combined model.

The BRidge algorithm allows for easy retrieval and interpretation of fitted parameters. For this reason, we used the model BRidge for this analysis. The model weights were obtained and averaged over CV folds for this analysis. These average values were then displayed for each ROI on a standard T1w template image. The weights indicate how important a feature was for, i.e. how much it contributed to, the final prediction in combination with the other features. This analysis was performed post-hoc.

Results

Model evaluation and comparison

Brain age was predicted using two reference models (dummy, pyment) and a set of models trained on three different feature sets: 5-HT2AR binding, GM volumes, and the combination of 5-HT2AR + GM data. The results for the best performing model in each feature set are visualized in Figure 2 and summarized in Table 2. A complete comparison of all models can be found in supplement S2.1. Overall, all models performed better than the dummy regressor and worse than the state-of-the-art software pyment. Figure 3 shows the mean prediction for each subject over the 20 iterations on each feature set for the models using rbfGPR. There was a strong correlation between chronological and predicted age and a moderate to strong negative correlation between PAD and chronological age.

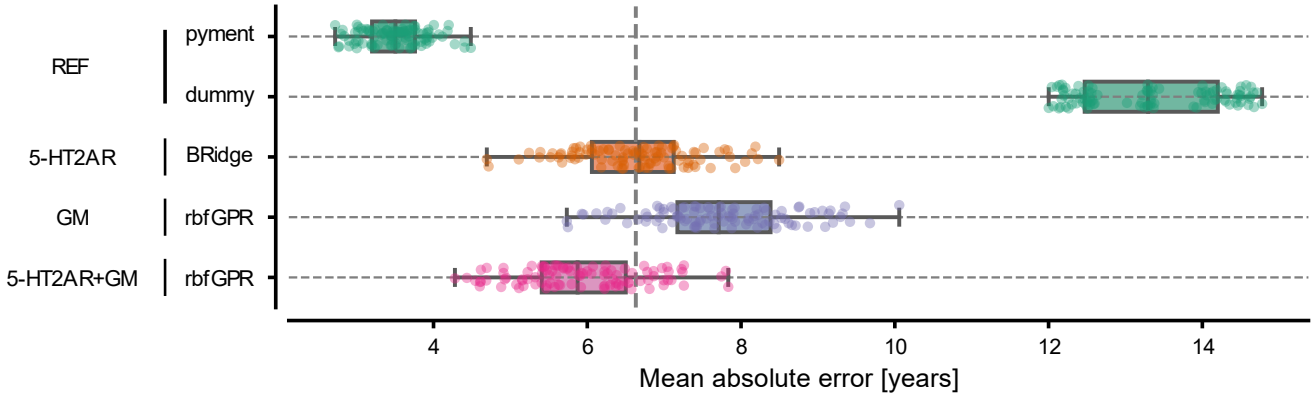

Figure 2: MAE for the best-performing models for each feature set. Each dot represents the MAE for one of the 100 CV iterations. The vertical dashed line marks the generalization error (mean over MAE for each fold) of the 5-HT2AR model.

The 5-HT2AR-based model showed that chronological age in healthy individuals could be predicted using regional 5-HT2AR binding with a generalization error of 6.63 years and a very strong correlation between predicted and chronological age (r=0.87). A moderate negative correlation between PAD and age (r=-0.49) was observed.

The GM-based model showed that chronological age in healthy individuals could be predicted using cortical and subcortical GM volumes with a generalization error of 7.76 years and a strong correlation (r=0.79) between predicted and chronological age. Further, a strong negative correlation between PAD and age (r=-0.7) was observed. Generally, the predictions were worse than those based on 5-HT2AR binding (p = 0.04).

The combined 5-HT2AR+GM-based model showed that chronological age in healthy individuals could be predicted using a combination of regional 5-HT2AR binding potentials and cortical and subcortical GM volumes, with a generalization error of 5.93 years and a very strong correlation (r=0.88) between predicted and chronological age. A weak negative correlation between PAD and age (r=-0.31) was observed. The predictions

were more accurate than those from both unimodal models. However, the statistical test comparing the 5-HT2AR based model with the combined model was not statistically significant (p = 0.14).

Table 2: The results of the best-performing model for the four experiments (Reference, 5-HT2AR, GM, 5-HT2AR + GM). Values are mean (std) over the 100 CV iterations for MAE, R2, r age, and r pad.

Modality	Model	Generalization Error (std)	R2 mean (std)	r age mean (std)	r pad mean (std)	p
Reference	pyment	3.5 (0.4)	0.93 (0.02)	0.96 (0.01)	-0.36 (0.1)	<<0.001
Reference	dummy	13.33 (0.91)	-0.01 (0.01)	-0.0 (0.0)	-1.0 (0.0)	<<0.001
5-HT2AR	BRidge	6.63 (0.78)	0.74 (0.07)	0.87 (0.04)	-0.49 (0.15)	-
GM	rbfGPR	7.76 (0.92)	0.6 (0.1)	0.79 (0.07)	-0.7 (0.08)	0.04
5-HT2AR + GM	rbfGPR	5.93 (0.82)	0.76 (0.1)	0.88 (0.04)	-0.31 (0.16)	0.14

r age - Pearson's r between predicted and chronological age; r pad - Pearson's r between PAD and chronological age; p values refer to tests of MAE in respective model vs MAE of the model trained on 5-HT2AR binding. Models: BRidge - Bayesian Ridge; rbfGPR - Gaussian Process Regression with Radiabl basis function kernel

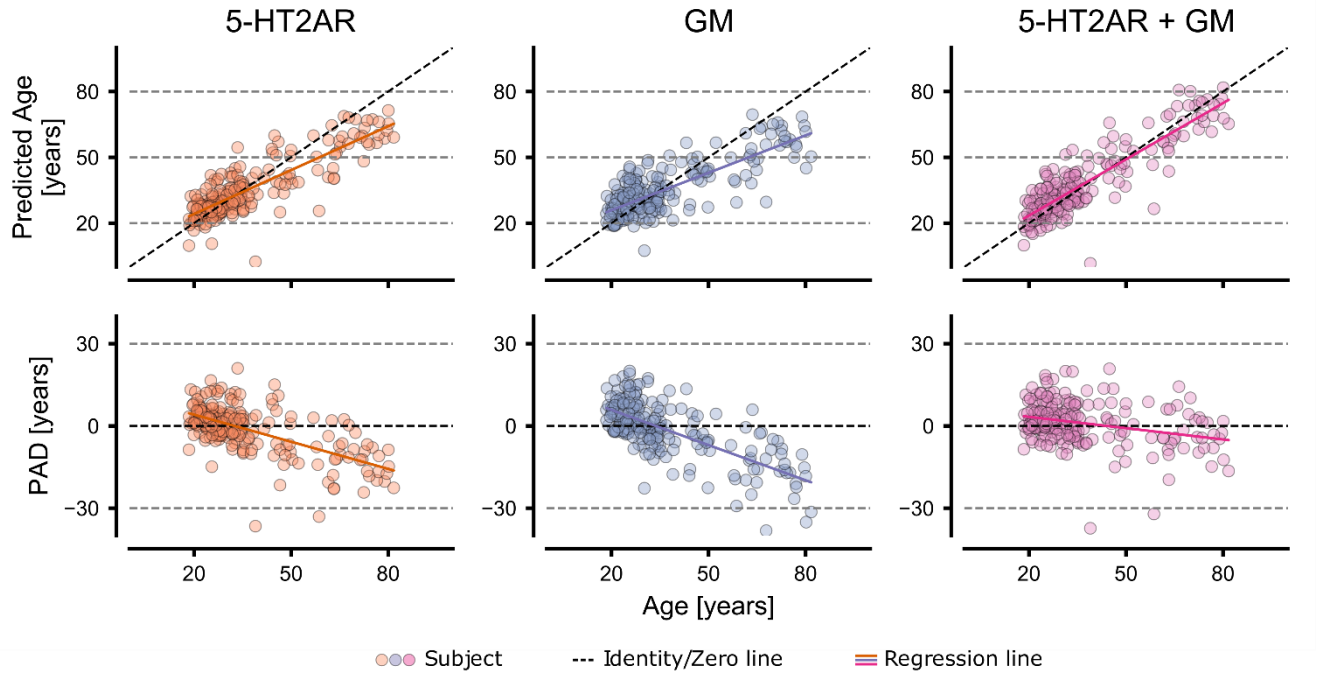

Figure 3: The predicted age and PAD vs. the chronological age for 5-HT2AR, GM, and 5-HT2AR+GM using rbfGPR. Each point represents a mean value over 100 CV iterations. The colored line represents the fitted regression line.

Feature importance and modality contribution

We also investigated the contributions of each modality and ROI to the brain age predictions. For the sake of clarity, the results for the Bayesian Ridge Regressor are used in this analysis, as it is a linear model and weights are easily derived. The correlation between the PAD from the models based on 5-HT2AR binding vs. GM volume feature sets was r=0.37 with R2=0.14 (Figure 4A). Figure 4B shows the weight of each feature set in the ensemble regressor, with 5-HT2AR-based predictions contributing more to the final outcome. The contribution from individual ROIs to the predicted age for each base model is visualized in Figure 4C and reported as boxplots in the supplement (Figure S2.2). For 5-HT2AR binding, the temporal and parietal lobes, insula, and putamen display the highest weights. The frontal lobe and insula contributed the most to age prediction based on GM volumes.

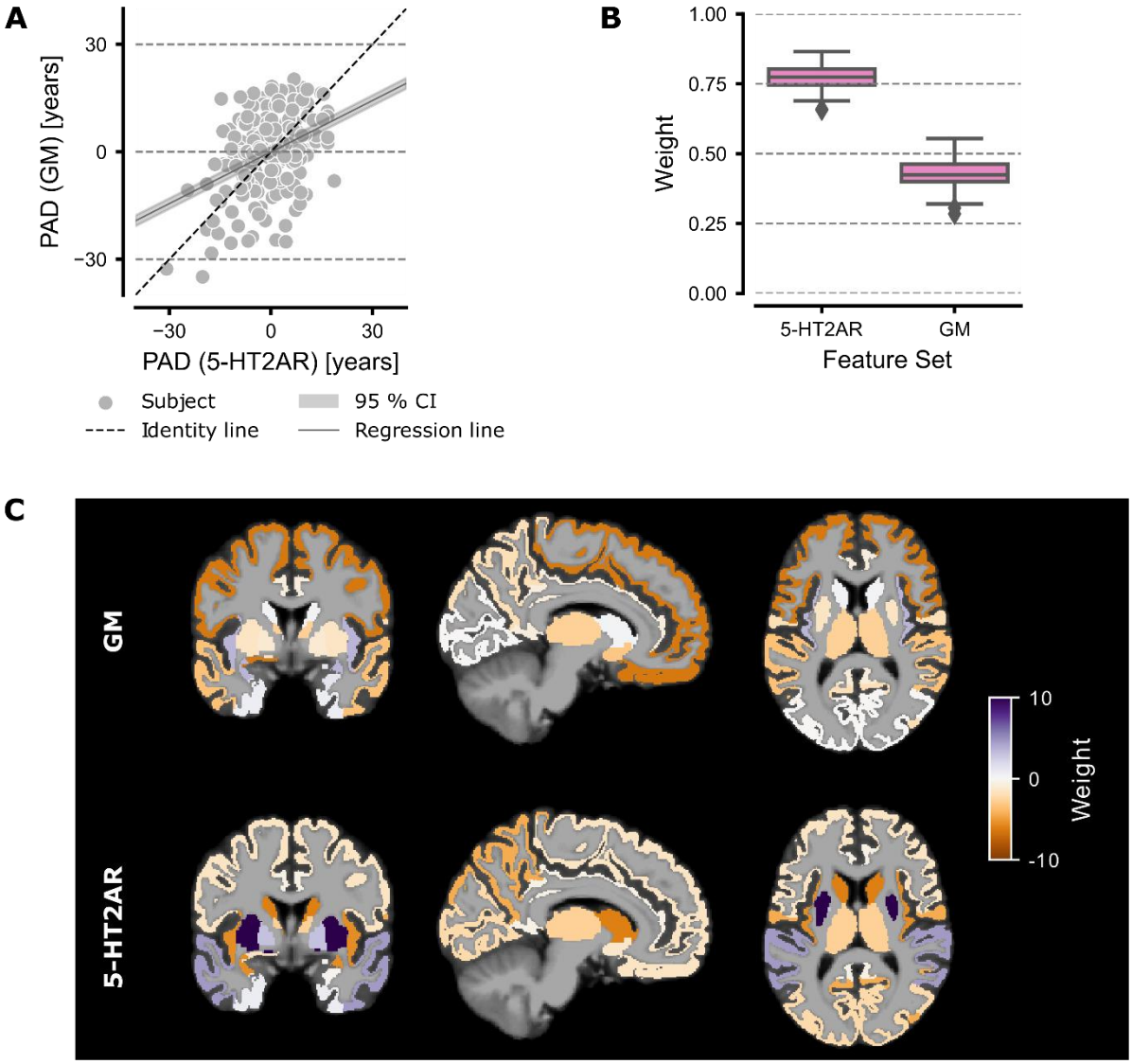

Figure 4: Comparison of 5-HT2AR vs GM based models. Panel **A)** The PAD from GM volume based predictions vs 5-HT2AR binding predictions. The solid gray line marks the fitted regression line, and the shaded area is the 95% confidence interval. Each point represents the mean PAD per subject averaged over all 100 CV iterations. Panel **B)** Boxplots showing the weights for the final ensemble regressor. Whiskers show 1.5 the interquartile range. Panel **C)** The weights for the ensemble base regressors (BRidge) overlaid on a MNI152 template brain.

Discussion

In this study, we investigated whether 5-HT2AR binding can be used as a putative biomarker for brain aging. For this purpose, we trained ML algorithms to predict chronological age based on regional binding estimates from 5-HT2AR PET images. We also trained ML models to predict chronological age from MRI GM volume estimates from the same regions, and we investigated whether combining both feature sets could improve overall performance. We find that ML algorithms trained on regional 5-HT2AR binding predicts chronological age with higher accuracy than algorithms using regional GM volume as input. Further, combining data from both feature sets tends to improve the overall performance, but not significantly compared to only the 5-HT2AR features.

The decline in 5-HT2AR binding with age is well described in the literature (Karrer et al., 2019). However, it is unclear to what extent the decline in binding estimates is caused by aging-related biology affecting the serotonin system or by structural changes affecting the PET signal. As the gray matter volume in most regions of the human brain decrease with age (Bethlehem et al., 2022), an increased "spill-out" of radioactivity will be registered by the PET system due to a limited image resolution (Meltzer et al., 1990). This could lead to lower observed binding estimates in brain regions while the true concentration of the 5-HT2AR is unchanged. In our data, age predictions based 5-HT2AR binding outperformed age predictions based on GM volumes. This indicates that the decline in 5-HT2AR binding is unlikely to be caused solely by radioactivity spill-out. In addition, combining the two feature sets showed increased accuracy over both unimodal approaches, indicating that the decline in 5-HT2AR binding contains unique information when predicting age beyond that of simple volumetric changes in the brain. Further, Figure 4C shows that different regions contribute to the respective age predictions for each feature set, indicating different aging patterns.

A significant correlation between PAD and chronological age was observed for all models. Such a correlation is a well-known issue discussed extensively in the brain age literature (Butler et al., 2021). Generally, a less accurate model predicting chronological age also shows a stronger negative correlation between PAD and chronological

age. Such an association is problematic since the PAD is supposed to reflect a higher (or lower) biological age and should not mirror any variance in chronological age. It is worth noting that the 5-HT2AR-based models showed a lower correlation between PAD and chronological age (Table 2). This shows that 5HT2AR binding might be more informative about the biological aging process than the GM volumes.

The predictions from the pre-trained MRI based model pyment showed high accuracy and outperformed all other tested methods. This is expected since pyment predicts age based on voxels from the entire brain and is pre-trained on an extensive training dataset (> 50,000 T1w MRI scans). Due to limitations in the sample size used in the current study (N=209), we decided to use regional (ROI) level data. Since white matter and the ventricle volumes change with age (Bethlehem et al., 2022), it is likely that including such features would have improved the predictions for the MRI-based models in our study. It should however be noted that, the observed results from both the 5-HT2AR binding and GM volume based models were on par with the accuracy of other brain age prediction models in the literature (Baecker et al., 2021; J. Cole et al., 2018; Guan et al., 2023). The improved accuracy of predictions based on 5-HT2AR binding over predictions based on GM volumes indicates that with increased sample size, brain age based on 5-HT2AR binding might outperform state-of-the-art MRI-based methods.

Our results are based on data from healthy individuals and consequently, we cannot know what the outcome would be in a patient population. Previous PET studies have revealed that compared to age-matched healthy controls, cerebral 5-HT2AR binding is reduced in mild cognitive impairment and in Alzheimer's disease (Hasselbalch et al., 2008; Marner et al., 2012), suggesting that a brain age model based on 5-HT2AR binding is able to predict neurodegeneration. 5-HT2AR neuroimaging could thus prove useful as a pathological aging biomarker for, e.g., early detection of neurodegenerative disorders and to evaluate putative neuroprotective interventions intended to slow age-related processes in the human brain.

Conclusion

We find that cerebral 5-HT2AR binding across different brain regions predicts chronological age more accurately than MR-based gray matter measurements. We propose machine learning models of 5-HT2AR binding data as an effective biomarker for aging- or disease-related changes in the human brain. Future studies should assess the diagnostic and prognostic value of 5-HT2AR -based age predictions in patients with neurodegenerative disorders.

Funding:

This work was supported by a Longevity Impetus Grant from the Norm Group. Jonas E. Svensson was supported by Region H (grant A7167). Pontus Plavén-Sigray was supported by the Swedish Research Council (grant 2021-00462).

Acknowledgements:

We would like to thank Kristoffer Hougaard Madsen for his valuable comments in his capacity as censor for the master's thesis preceding this manuscript.

Conflict of interest:

The authors declare no conflicts of interest in relation to this work.

References

Adams, K.H., Pinborg, L.H., Svarer, C., Hasselbalch, S.G., Holm, S., Haugbøl, S., Madsen, K., Frøkjær, V., Martiny, L., Paulson, O.B., Knudsen, G.M., 2004. A database of [18F]-altanserin binding to 5-HT2A receptors in normal volunteers: normative data and relationship to physiological and demographic variables. NeuroImage 21, 1105–1113. https://doi.org/10.1016/j.neuroimage.2003.10.046

Bäckman, L., Karlsson, S., Fischer, H., Karlsson, P., Brehmer, Y., Rieckmann, A., MacDonald, S.W.S., Farde, L., Nyberg, L., 2011. Dopamine D1 receptors and age differences in brain activation during working memory. Neurobiol. Aging 32, 1849–1856. https://doi.org/10.1016/j.neurobiolaging.2009.10.018

Baecker, L., Dafflon, J., Costa, P.F., Garcia-Dias, R., Vieira, S., Scarpazza, C., Calhoun, V.D., Sato, J.R., Mechelli, A., Pinaya, W.H.L., 2021. Brain age prediction: A comparison between machine learning models using region- and voxel-based morphometric data. Hum. Brain Mapp. 42, 2332–2346. https://doi.org/10.1002/hbm.25368

Bashyam, V.M., Erus, G., Doshi, J., Habes, M., Nasralah, I., Truelove-Hill, M., Srinivasan, D., Mamourian, L., Pomponio, R., Fan, Y., Launer, L.J., Masters, C.L., Maruff, P., Zhuo, C., Völzke, H., Johnson, S.C., Fripp, J., Koutsouleris, N., Satterthwaite, T.D., Wolf, D., Gur, R.E., Gur, R.C., Morris, J., Albert, M.S., Grabe, H.J., Resnick, S., Nick Bryan, R., Wolk, D.A., Shou, H., Davatzikos, C., 2020. MRI signatures of brain age and disease over the lifespan based on a deep brain network and 14 468 individuals worldwide. Brain 143, 2312–2324. https://doi.org/10.1093/brain/awaa160

Benavoli, A., Corani, G., Demsar, J., Zaffalon, M., 2017. Time for a change: a tutorial for comparing multiple classifiers through Bayesian analysis.

Bethlehem, R.A.I., Seidlitz, J., White, S.R., Vogel, J.W., Anderson, K.M., Adamson, C., Adler, S., Alexopoulos, G.S., Anagnostou, E., Areces-Gonzalez, A., Astle, D.E., Auyeung, B., Ayub, M., Bae, J., Ball, G., Baron-Cohen, S., Beare, R., Bedford, S.A., Benegal, V., Beyer, F., Blangero, J., Blesa Cábez, M., Boardman, J.P., Borzage, M., Bosch-Bayard, J.F., Bourke, N., Calhoun, V.D., Chakravarty, M.M., Chen, C., Chertavian, C., Chetelat, G., Chong, Y.S., Cole, J.H., Corvin, A., Costantino, M., Courchesne, E., Crivello, F., Cropley, V.L., Crosbie, J., Crossley, N., Delarue, M., Delorme, R., Desrivieres, S., Devenyi, G.A., Di Biase, M.A., Dolan, R., Donald, K.A., Donohoe, G., Dunlop, K., Edwards, A.D., Elison, J.T., Ellis, C.T., Elman, J.A., Eyler, L., Fair, D.A., Feczko, E., Fletcher, P.C., Fonagy, P., Franz, C.E., Galan-Garcia, L., Gholipour, A., Giedd, J., Gilmore, J.H., Glahn, D.C., Goodyer, I.M., Grant, P.E., Groenewold, N.A., Gunning, F.M., Gur, R.E., Gur, R.C., Hammill, C.F., Hansson, O., Hedden, T., Heinz, A., Henson, R.N., Heuer, K., Hoare, J., Holla, B., Holmes, A.J., Holt, R., Huang, H., Im, K., Ipser, J., Jack, C.R., Jackowski, A.P., Jia, T., Johnson, K.A., Jones, P.B., Jones, D.T., Kahn, R.S., Karlsson, H., Karlsson, L., Kawashima, R., Kelley, E.A., Kern, S., Kim, K.W., Kitzbichler, M.G., Kremen, W.S., Lalonde, F., Landeau, B., Lee, S., Lerch, J., Lewis, J.D., Li, J., Liao, W., Liston, C., Lombardo, M.V., Lv, J., Lynch, C., Mallard, T.T., Marcelis, M., Markello, R.D., Mathias, S.R., Mazoyer, B., McGuire, P., Meaney, M.J., Mechelli, A., Medic, N., Misic, B., Morgan, S.E., Mothersill, D., Nigg, J., Ong, M.Q.W., Ortinau, C., Ossenkoppele, R., Ouyang, M., Palaniyappan, L., Paly, L., Pan, P.M., Pantelis, C., Park, M.M., Paus, T., Pausova, Z., Paz-Linares, D., Pichet Binette, A., Pierce, K., Qian, X., Qiu, J., Qiu, A., Raznahan, A., Rittman, T., Rodrigue, A., Rollins, C.K., Romero-Garcia, R., Ronan, L., Rosenberg, M.D., Rowitch, D.H., Salum, G.A., Satterthwaite, T.D., Schaare, H.L., Schachar, R.J., Schultz, A.P., Schumann, G., Schöll, M., Sharp, D., Shinohara, R.T., Skoog, I., Smyser, C.D., Sperling, R.A., Stein, D.J., Stolicyn, A., Suckling, J., Sullivan, G., Taki, Y., Thyreau, B., Toro, R., Traut, N., Tsvetanov, K.A., Turk-Browne, N.B., Tuulari, J.J., Tzourio, C., Vachon-Presseau, É., Valdes-Sosa, M.J., Valdes-Sosa, P.A., Valk, S.L., van Amelsvoort, T., Vandekar, S.N., Vasung, L., Victoria, L.W., Villeneuve, S., Villringer, A., Vértes, P.E., Wagstyl, K., Wang, Y.S., Warfield, S.K., Warrier, V., Westman, E., Westwater, M.L., Whalley, H.C., Witte, A.V., Yang, N., Yeo, B., Yun, H., Zalesky, A., Zar, H.J., Zettergren, A., Zhou, J.H., Ziauddeen, H., Zugman, A., Zuo, X.N., Rowe, C., Frisoni, G.B., Binette,

A.P., Bullmore, E.T., Alexander-Bloch, A.F., 2022. Brain charts for the human lifespan. Nature. https://doi.org/10.1038/s41586-022-04554-y

Buckner, R.L., Head, D., Parker, J., Fotenos, A.F., Marcus, D., Morris, J.C., Snyder, A.Z., 2004. A unified approach for morphometric and functional data analysis in young, old, and demented adults using automated atlas-based head size normalization: reliability and validation against manual measurement of total intracranial volume. NeuroImage 23, 724–738. https://doi.org/10.1016/j.neuroimage.2004.06.018

Butler, E.R., Chen, A., Ramadan, R., Le, T.T., Ruparel, K., Moore, T.M., Satterthwaite, T.D., Zhang, F., Shou, H., Gur, R.C., Nichols, T.E., Shinohara, R.T., 2021. Pitfalls in brain age analyses. Hum. Brain Mapp. 42, 4092–4101. https://doi.org/10.1002/hbm.25533

Campbell, M.J. (Ed.), 2021. Statistics at Square One, 1st ed. Wiley. https://doi.org/10.1002/9781119402350

Cole, J., Franke, K., Cherbuin, N., 2018. Quantification of the biological age of the brain using neuroimaging. https://doi.org/10.31219/osf.io/3b6zu

Cole, J.H., Poudel, R.P.K., Tsagkrasoulis, D., Caan, M.W.A., Steves, C., Spector, T.D., Montana, G., 2017. Predicting brain age with deep learning from raw imaging data results in a reliable and heritable biomarker. NeuroImage 163, 115–124. https://doi.org/10.1016/j.neuroimage.2017.07.059

Cole, J.H., Ritchie, S.J., Bastin, M.E., Valdés Hernández, M.C., Muñoz Maniega, S., Royle, N., Corley, J., Pattie, A., Harris, S.E., Zhang, Q., Wray, N.R., Redmond, P., Marioni, R.E., Starr, J.M., Cox, S.R., Wardlaw, J.M., Sharp, D.J., Deary, I.J., 2018. Brain age predicts mortality. Mol. Psychiatry 23, 1385–1392. https://doi.org/10.1038/mp.2017.62

Cox, S.R., Ritchie, S.J., Tucker-Drob, E.M., Liewald, D.C., Hagenaars, S.P., Davies, G., Wardlaw, J.M., Gale, C.R., Bastin, M.E., Deary, I.J., 2016. Ageing and brain white matter structure in 3,513 UK Biobank participants. Nat. Commun. 7, 13629. https://doi.org/10.1038/ncomms13629

Desikan, R.S., Ségonne, F., Fischl, B., Quinn, B.T., Dickerson, B.C., Blacker, D., Buckner, R.L., Dale, A.M., Maguire, R.P., Hyman, B.T., Albert, M.S., Killiany, R.J., 2006. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. NeuroImage 31, 968–980. https://doi.org/10.1016/j.neuroimage.2006.01.021

Dörfel, R.P., Arenas-Gomez, J.M., Fisher, P.M., Ganz, M., Knudsen, G.M., Svensson, J.E., Plavén-Sigray, P., 2023. Prediction of brain age using structural magnetic resonance imaging: A comparison of accuracy and test–retest reliability of publicly available software packages. Hum. Brain Mapp. n/a. https://doi.org/10.1002/hbm.26502

Ettrup, A., da Cunha-Bang, S., McMahon, B., Lehel, S., Dyssegaard, A., Skibsted, A.W., Jørgensen, L.M., Hansen, M., Baandrup, A.O., Bache, S., Svarer, C., Kristensen, J.L., Gillings, N., Madsen, J., Knudsen, G.M., 2014. Serotonin 2A receptor agonist binding in the human brain with [11C]Cimbi-36. J. Cereb. Blood Flow Metab. 34, 1188–1196. https://doi.org/10.1038/jcbfm.2014.68

Ettrup, A., Svarer, C., McMahon, B., da Cunha-Bang, S., Lehel, S., Møller, K., Dyssegaard, A., Ganz, M., Beliveau, V., Jørgensen, L.M., Gillings, N., Knudsen, G.M., 2016. Serotonin 2A receptor agonist binding in the human brain with [11C]Cimbi-36: Test–retest reproducibility and head-to-head comparison with the antagonist [18F]altanserin. NeuroImage 130, 167–174. https://doi.org/10.1016/j.neuroimage.2016.02.001

Fischl, B., 2012. FreeSurfer. NeuroImage 62, 774–781. https://doi.org/10.1016/j.neuroimage.2012.01.021

Fischl, B., Salat, D.H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., van der Kouwe, A., Killiany, R., Kennedy, D., Klaveness, S., Montillo, A., Makris, N., Rosen, B., Dale, A.M., 2002. Whole Brain Segmentation: Automated Labeling of Neuroanatomical Structures in the Human Brain. Neuron 33, 341–355. https://doi.org/10.1016/S0896-6273(02)00569-X

Franke, K., Ziegler, G., Klöppel, S., Gaser, C., 2010. Estimating the age of healthy subjects from T1-weighted MRI scans using kernel methods: Exploring the influence of various parameters. NeuroImage 50, 883–892. https://doi.org/10.1016/j.neuroimage.2010.01.005

Frokjaer, V.G., Erritzoe, D., Madsen, J., Paulson, O.B., Knudsen, G.M., 2009. Gender and the use of hormonal contraception in women are not associated with cerebral cortical 5-HT 2A receptor binding. Neuroscience 163, 640–645. https://doi.org/10.1016/j.neuroscience.2009.06.052

Gaser, C., Franke, K., Klöppel, S., Koutsouleris, N., Sauer, H., 2013. BrainAGE in Mild Cognitive Impaired Patients: Predicting the Conversion to Alzheimer's Disease. PLoS ONE 8. https://doi.org/10.1371/journal.pone.0067346

Guan, S., Jiang, R., Meng, C., Biswal, B., 2023. Brain age prediction across the human lifespan using multimodal MRI data. GeroScience. https://doi.org/10.1007/s11357-023-00924-0

Han, L.K.M., Dinga, R., Hahn, T., Ching, C.R.K., Eyler, L.T., Aftanas, L., Aghajani, M., Aleman, A., Baune, B.T., Berger, K., Brak, I., Filho, G.B., Carballedo, A., Connolly, C.G., Couvy-Duchesne, B., Cullen, K.R., Dannlowski, U., Davey, C.G., Dima, D., Duran, F.L.S., Enneking, V., Filimonova, E., Frenzel, S., Frodl, T., Fu, C.H.Y., Godlewska, B.R., Gotlib, I.H., Grabe, H.J., Groenewold, N.A., Grotegerd, D., Gruber, O., Hall, G.B., Harrison, B.J., Hatton, S.N., Hermesdorf, M., Hickie, I.B., Ho, T.C., Hosten, N., Jansen, A., Kähler, C., Kircher, T., Klimes-Dougan, B., Krämer, B., Krug, A., Lagopoulos, J., Leenings, R., MacMaster, F.P., MacQueen, G., McIntosh, A., McLellan, Q., McMahon, K.L., Medland, S.E., Mueller, B.A., Mwangi, B., Osipov, E., Portella, M.J., Pozzi, E., Reneman, L., Repple, J., Rosa, P.G.P., Sacchet, M.D., Sämann, P.G., Schnell, K., Schrantee, A., Simulionyte, E., Soares, J.C., Sommer, J., Stein, D.J., Steinsträter, O., Strike, L.T., Thomopoulos, S.I., van Tol, M.J., Veer, I.M., Vermeiren, R.R.J.M., Walter, H., van der Wee, N.J.A., van der Werff, S.J.A., Whalley, H., Winter, N.R., Wittfeld, K., Wright, M.J., Wu, M.J., Völzke, H., Yang, T.T., Zannias, V., de Zubicaray, G.I., Zunta-Soares, G.B., Abé, C., Alda, M., Andreassen, O.A., Bøen, E., Bonnin, C.M., Canales-Rodriguez, E.J., Cannon, D., Caseras, X., Chaim-Avancini, T.M., Elvsåshagen, T., Favre, P., Foley, S.F., Fullerton, J.M., Goikolea, J.M., Haarman, B.C.M., Hajek, T., Henry, C., Houenou, J., Howells, F.M., Ingvar, M., Kuplicki, R., Lafer, B., Landén, M., Machado-Vieira, R., Malt, U.F., McDonald, C., Mitchell, P.B., Nabulsi, L., Otaduy, M.C.G., Overs, B.J., Polosan, M., Pomarol-Clotet, E., Radua, J., Rive, M.M., Roberts, G., Ruhe, H.G., Salvador, R., Sarró, S., Satterthwaite, T.D., Savitz, J., Schene, A.H., Schofield, P.R., Serpa, M.H., Sim, K., Soeiro-de-Souza, M.G., Sutherland, A.N., Temmingh, H.S., Timmons, G.M., Uhlmann, A., Vieta, E., Wolf, D.H., Zanetti, M.V., Jahanshad, N., Thompson, P.M., Veltman, D.J., Penninx, B.W.J.H., Marquand, A.F., Cole, J.H., Schmaal, L., 2021. Brain aging in major depressive disorder: results from the ENIGMA major depressive disorder working group. Mol. Psychiatry 26, 5124–5139. https://doi.org/10.1038/s41380-020-0754-0

Hasselbalch, S.G., Madsen, K., Svarer, C., Pinborg, L.H., Holm, S., Paulson, O.B., Waldemar, G., Knudsen, G.M., 2008. Reduced 5-HT2A receptor binding in patients with mild cognitive impairment. Neurobiol. Aging 29, 1830–1838. https://doi.org/10.1016/j.neurobiolaging.2007.04.011

Higgins-Chen, A.T., Thrush, K.L., Levine, M.E., 2021. Aging biomarkers and the brain. Semin. Cell Dev. Biol. 116, 180–193. https://doi.org/10.1016/j.semcdb.2021.01.003

Hou, Y., Dan, X., Babbar, M., Wei, Y., Hasselbalch, S.G., Croteau, D.L., Bohr, V.A., 2019. Ageing as a risk factor for neurodegenerative disease. Nat. Rev. Neurol. 15, 565–581. https://doi.org/10.1038/s41582-019-0244-7

Ichise, M., Liow, J.-S., Lu, J.-Q., Takano, A., Model, K., Toyama, H., Suhara, T., Suzuki, K., Innis, R.B., Carson, R.E., 2003. Linearized Reference Tissue Parametric Imaging Methods: Application to [^{11} C]DASB Positron Emission Tomography Studies of the Serotonin Transporter in Human Brain. J. Cereb. Blood Flow Metab. 23, 1096–1112. https://doi.org/10.1097/01.WCB.0000085441.37552.CA

Karrer, T.M., McLaughlin, C.L., Guaglianone, C.P., Samanez-Larkin, G.R., 2019. Reduced serotonin receptors and transporters in normal aging adults: a meta-analysis of PET and SPECT imaging studies. Neurobiol. Aging 80, 1–10. https://doi.org/10.1016/j.neurobiolaging.2019.03.021

Kaufmann, T., van der Meer, D., Doan, N.T., Schwarz, E., Lund, M.J., Agartz, I., Alnæs, D., Barch, D.M., Baur-Streubel, R., Bertolino, A., Bettella, F., Beyer, M.K., Bøen, E., Borgwardt, S., Brandt, C.L., Buitelaar, J., Celius, E.G., Cervenka, S., Conzelmann, A., Córdova-Palomera, A., Dale, A.M., de Quervain, D.J.F.,

Carlo, P.D., Djurovic, S., Dørum, E.S., Eisenacher, S., Elvsåshagen, T., Espeseth, T., Fatouros-Bergman, H., Flyckt, L., Franke, B., Frei, O., Haatveit, B., Håberg, A.K., Harbo, H.F., Hartman, C.A., Heslenfeld, D., Hoekstra, P.J., Høgestøl, E.A., Jernigan, T.L., Jonassen, R., Jönsson, E.G., Farde, L., Flyckt, L., Engberg, G., Erhardt, S., Fatouros-Bergman, H., Cervenka, S., Schwieler, L., Piehl, F., Agartz, I., Collste, K., Victorsson, P., Malmqvist, A., Hedberg, M., Orhan, F., Kirsch, P., Kłoszewska, I., Kolskår, K.K., Landrø, N.I., Hellard, S.L., Lesch, K.P., Lovestone, S., Lundervold, A., Lundervold, A.J., Maglanoc, L.A., Malt, U.F., Mecocci, P., Melle, I., Meyer-Lindenberg, A., Moberget, T., Norbom, L.B., Nordvik, J.E., Nyberg, L., Oosterlaan, J., Papalino, M., Papassotiropoulos, A., Pauli, P., Pergola, G., Persson, K., Richard, G., Rokicki, J., Sanders, A.M., Selbæk, G., Shadrin, A.A., Smeland, O.B., Soininen, H., Sowa, P., Steen, V.M., Tsolaki, M., Ulrichsen, K.M., Vellas, B., Wang, L., Westman, E., Ziegler, G.C., Zink, M., Andreassen, O.A., Westlye, L.T., 2019. Common brain disorders are associated with heritable patterns of apparent aging of the brain. Nat. Neurosci. 22, 1617–1623. https://doi.org/10.1038/s41593-019-0471-7

Klein, A., Tourville, J., 2012. 101 Labeled Brain Images and a Consistent Human Cortical Labeling Protocol. Front. Neurosci. 6. https://doi.org/10.3389/fnins.2012.00171

Knudsen, G.M., Jensen, P.S., Erritzoe, D., Baaré, W.F.C., Ettrup, A., Fisher, P.M., Gillings, N., Hansen, H.D., Hansen, L.K., Hasselbalch, S.G., Henningsson, S., Herth, M.M., Holst, K.K., Iversen, P., Kessing, L.V., Macoveanu, J., Madsen, K.S., Mortensen, E.L., Nielsen, F.Å., Paulson, O.B., Siebner, H.R., Stenbæk, D.S., Svarer, C., Jernigan, T.L., Strother, S.C., Frokjaer, V.G., 2016. The Center for Integrated Molecular Brain Imaging (Cimbi) database. NeuroImage 124, 1213–1219. https://doi.org/10.1016/j.neuroimage.2015.04.025

Lemaire, C., Cantineau, R., Guillaume, M., Plenevaux, A., Christiaens, L., 1991. Study of Serotonin Receptors with PET: Radiolabeling and In Vivo Biologic Behavior.

Leonardsen, E.H., Peng, H., Kaufmann, T., Agartz, I., Andreassen, O.A., Celius, E.G., Espeseth, T., Harbo, H.F., Høgestøl, E.A., Lange, A.-M. de, Marquand, A.F., Vidal-Piñeiro, D., Roe, J.M., Selbæk, G., Sørensen, Ø., Smith, S.M., Westlye, L.T., Wolfers, T., Wang, Y., 2022. Deep neural networks learn general and clinically relevant representations of the ageing brain. NeuroImage 256, 119210. https://doi.org/10.1016/j.neuroimage.2022.119210

Leysen, J.E., 2004. 5-HT2 Receptors. Curr. Drug Targets - CNS Neurol. Disord. 3, 11–26. https://doi.org/10.2174/1568007043482598

Liem, F., Varoquaux, G., Kynast, J., Beyer, F., Kharabian Masouleh, S., Huntenburg, J.M., Lampe, L., Rahim, M., Abraham, A., Craddock, R.C., Riedel-Heller, S., Luck, T., Loeffler, M., Schroeter, M.L., Witte, A.V., Villringer, A., Margulies, D.S., 2017. Predicting brain-age from multimodal imaging data captures cognitive impairment. NeuroImage 148, 179–188. https://doi.org/10.1016/j.neuroimage.2016.11.005

Marner, L., Frokjaer, V.G., Kalbitzer, J., Lehel, S., Madsen, K., Baaré, W.F.C., Knudsen, G.M., Hasselbalch, S.G., 2012. Loss of serotonin 2A receptors exceeds loss of serotonergic projections in early Alzheimer's disease: a combined [11 C]DASB and [18 F]altanserin-PET study. https://doi.org/10.1016/j.neurobiolaging.2010.03.023

Mattson, M.P., Arumugam, T.V., 2018. Hallmarks of Brain Aging: Adaptive and Pathological Modification by Metabolic States. Cell Metab. 27, 1176–1199. https://doi.org/10.1016/j.cmet.2018.05.011

Meltzer, C.C., Leal, J.P., Mayberg, H.S., Wagner, H.N.J., Frost, J.J., 1990. Correction of PET Data for Partial Volume Effects in Human Cerebral Cortex by MR Imaging. J. Comput. Assist. Tomogr. 14, 561.

Moqri, M., Herzog, C., Poganik, J.R., Justice, J., Belsky, D.W., Higgins-Chen, A., Moskalev, A., Fuellen, G., Cohen, A.A., Bautmans, I., Widschwendter, M., Ding, J., Fleming, A., Mannick, J., Han, J.-D.J., Zhavoronkov, A., Barzilai, N., Kaeberlein, M., Cummings, S., Kennedy, B.K., Ferrucci, L., Horvath, S., Verdin, E., Maier, A.B., Snyder, M.P., Sebastiano, V., Gladyshev, V.N., 2023. Biomarkers of aging for the identification and evaluation of longevity interventions. Cell 186, 3758–3775. https://doi.org/10.1016/j.cell.2023.08.003

Moses-Kolko, E.L., Price, J.C., Shah, N., Berga, S., Sereika, S.M., Fisher, P.M., Coleman, R., Becker, C., Mason, N.S., Loucks, T., Meltzer, C.C., 2011. Age, Sex, and Reproductive Hormone Effects on Brain Serotonin-1A and Serotonin-2A Receptor Binding in a Healthy Population. Neuropsychopharmacology 36, 2729–2740. https://doi.org/10.1038/npp.2011.163

Nadeau, C., 2003. Inference for the Generalization Error.

Niccoli, T., Partridge, L., 2012. Ageing as a Risk Factor for Disease. Curr. Biol. 22, R741–R752. https://doi.org/10.1016/j.cub.2012.07.024

Nielsen, A.N., Greene, D.J., Gratton, C., Dosenbach, N.U.F., Petersen, S.E., Schlaggar, B.L., 2019. Evaluating the Prediction of Brain Maturity From Functional Connectivity After Motion Artifact Denoising. Cereb. Cortex 29, 2455–2469. https://doi.org/10.1093/cercor/bhy117

Pazos, A., Probst, A., Palacios, J.M., 1987. Serotonin receptors in the human brain—IV. Autoradiographic mapping of serotonin-2 receptors. Neuroscience 21, 123–139. https://doi.org/10.1016/0306-4522(87)90327-7

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., Duchesnay, É., 2011. Scikit-learn: Machine learning in Python. J. Mach. Learn. Res. 12, 2825–2830.

Pinborg, L.H., Adams, K.H., Svarer, C., Holm, S., Hasselbalch, S.G., Haugbøl, S., Madsen, J., Knudsen, G.M., 2003. Quantification of 5-HT2A Receptors in the Human Brain Using [18F]Altanserin-PET and the Bolus/Infusion Approach. J. Cereb. Blood Flow Metab. 23, 985–996. https://doi.org/10.1097/01.WCB.0000074092.59115.23

Properzi, M.J., Buckley, R.F., Chhatwal, J.P., Donohue, M.C., Lois, C., Mormino, E.C., Johnson, K.A., Sperling, R.A., Schultz, A.P., 2019. Nonlinear Distributional Mapping (NoDiM) for harmonization across amyloid-PET radiotracers. NeuroImage 186, 446–454. https://doi.org/10.1016/j.neuroimage.2018.11.019

Rose, M.R., 2009. Adaptation, aging, and genomic information. Aging 1, 444–450.

Rosier, A., Dupont, P., Peuskens, J., Bormans, G., Vandenberghe, R., Maes, M., de Groot, T., Schiepers, C., Verbruggen, A., Mortelmans, L., 1996. Visualisation of loss of 5-HT2A receptors with age in healthy volunteers using [18F]altanserin and positron emission tomographic imaging. Psychiatry Res. Neuroimaging 68, 11–22. https://doi.org/10.1016/S0925-4927(96)02806-5

Sauver, J.L.S., Boyd, C.M., Grossardt, B.R., Bobo, W.V., Rutten, L.J.F., Roger, V.L., Ebbert, J.O., Therneau, T.M., Yawn, B.P., Rocca, W.A., 2015. Risk of developing multimorbidity across all ages in an historical cohort study: differences by sex and ethnicity. BMJ Open 5, e006413. https://doi.org/10.1136/bmjopen-2014-006413

Schuitemaker, A., van der Doef, T.F., Boellaard, R., van der Flier, W.M., Yaqub, M., Windhorst, A.D., Barkhof, F., Jonker, C., Kloet, R.W., Lammertsma, A.A., Scheltens, P., van Berckel, B.N.M., 2012. Microglial activation in healthy aging. Neurobiol. Aging 33, 1067–1072. https://doi.org/10.1016/j.neurobiolaging.2010.09.016

Sheline, Y.I., Mintun, M.A., Moerlein, S.M., Snyder, A.Z., 2002. Greater Loss of 5-HT2A Receptors in Midlife Than in Late Life. Am. J. Psychiatry 159, 430–435. https://doi.org/10.1176/appi.ajp.159.3.430

Talbot, P.S., Slifstein, M., Hwang, D.-R., Huang, Y., Scher, E., Abi-Dargham, A., Laruelle, M., 2012. Extended characterisation of the serotonin 2A (5-HT2A) receptor-selective PET radiotracer 11C-MDL100907 in humans: Quantitative analysis, test–retest reproducibility, and vulnerability to endogenous 5-HT tone. NeuroImage 59, 271–285. https://doi.org/10.1016/j.neuroimage.2011.07.001

Varnäs, K., Halldin, C., Hall, H., 2004. Autoradiographic distribution of serotonin transporters and receptor subtypes in human brain. Hum. Brain Mapp. 22, 246–260. https://doi.org/10.1002/hbm.20035

Varoquaux, G., Raamana, P.R., Engemann, D.A., Hoyos-Idrobo, A., Schwartz, Y., Thirion, B., 2017. Assessing and tuning brain decoders: Cross-validation, caveats, and guidelines. NeuroImage 145, 166–179. https://doi.org/10.1016/j.neuroimage.2016.10.038

Versijpt, J., Van Laere, K.J., Dumont, F., Decoo, D., Vandecapelle, M., Santens, P., Goethals, I., Audenaert, K., Slegers, G., Dierckx, R.A., Korf, J., 2003. Imaging of the 5-HT2A system: age-, gender-, and Alzheimer's disease-related findings. Neurobiol. Aging 24, 553–561. https://doi.org/10.1016/S0197-4580(02)00137-9

Wagen, A.Z., Coath, W., Keshavan, A., James, S.-N., Parker, T.D., Lane, C.A., Buchanan, S.M., Keuss, S.E., Storey, M., Lu, K., Macdougall, A., Murray-Smith, H., Freiberger, T., Cash, D.M., Malone, I.B., Barnes, J., Sudre, C.H., Wong, A., Pavisic, I.M., Street, R., Crutch, S.J., Escott-Price, V., Leonenko, G., Zetterberg, H., Wellington, H., Heslegrave, A., Barkhof, F., Richards, M., Fox, N.C., Cole, J.H., Schott, J.M., 2022. Life course, genetic, and neuropathological associations with brain age in the 1946 British Birth Cohort: a population-based study. Lancet Healthy Longev. 3, e607–e616. https://doi.org/10.1016/S2666-7568(22)00167-2

Wolpert, D.H., 1992. Stacked generalization. Neural Netw. 5, 241–259. https://doi.org/10.1016/S0893-6080(05)80023-1

Wong, D.F., Wagner, H.N., Dannals, R.F., Links, J.M., Frost, J.J., Ravert, H.T., Wilson, A.A., Rosenbaum, A.E., Gjedde, A., Douglass, K.H., Petronis, J.D., Folstein, M.F., Toung, J.K.T., Burns, H.D., Kuhar, M.J., 1984. Effects of age on dopamine and serotonin receptors measured by positron tomography in the living human brain. Science 226, 1393–1396.

Woods, R.P., Cherry, S.R., Mazziotta, J.C., 1992. Rapid Automated Algorithm for Aligning and Reslicing PET Images. J. Comput. Assist. Tomogr. 16, 620.