Evaluation of Lentiform Nuclei Volume in Healthy Individuals Who Exercise Regularly Using the Semi-automatic Tracing Technique

Funda Aksu[1]*, Selim Karabekir[2], Nuri Karabay[3], Erkan Gunay[4]

Abstract
This study conducted volumetric analyses on the lentiform nuclei, specifically the putamen and globus pallidus, in healthy individuals. The analyses considered age, gender, and body mass index. The measurements were performed separately for each hemisphere. This study aimed to examine potential differences in regular exercising men and women based on age, gender, and body mass index (BMI) through volumetric analysis of lentiform nuclei. A total of 16 individuals (7 female and 9 male) who exercise regularly were randomly selected for this study. The cross-sections were assessed to determine the volumes of the left and right lentiform nuclei in relation to age, gender, and body mass index for each participant. Statistical analysis was performed using the semi-automatic tracking method in MRI. Both genders showed higher left lentiform nuclei volume and putamen volume, while the right globus pallidus volume was also higher. However, these differences were not statistically significant. The volume of the lentiform nuclei was found to be greater in women compared to men, although this difference was not statistically significant. A significant positive correlation was observed between the volume of the right globus pallidus and age in men. A positive correlation was observed between right putamen volume, left lentiform nuclei volume, and left putamen volume with body mass index in all subjects. However, this correlation was not statistically significant. The data may contribute to the creation of a comprehensive database that includes typical lentiform nuclei and potential asymmetrical alterations in brain morphology. Furthermore, it has the potential to offer valuable insights to clinicians and anatomists.
Keywords: Lentiform Nuclei; Putamen; Globus Pallidus; Semi-Automatic Tracing Technique; Morphology.

Introduction

The basal nuclei are comprised of five pairs of deep brain hemispheres nuclei, namely the putamen, nucleus caudatus, substantia nigra, nucleus subthalamicus and globus pallidus. The structures known as the putamen, globus pallidus and nucleus caudatus are together referred to as the "corpus striatum" (Saunders, Huang, & Sabatini, 2016; Standring et al., 2005). The lentiform nucleus (LN) is a lens-shaped structure located in the basal ganglia of the corpus striatum. It consists of two capsules, one internal and one exterior, and is composed of three components: the internal and external globus pallidus (Gp) and the putamen. (P) (Standring et al., 2005).
Prior research has demonstrated the involvement of the basal nuclei in mental and emotional functions, as well as motor movement coordination (Andreasen et al., 1996; Standring et al., 2005). The corpus striatum is involved in the acquisition and maintenance of motor skills. Several studies have shown that motor learning induces neuronal changes in the corpus striatum (Hänggi et al., 2015; Park et al., 2009; Standring et al., 2005).
The LN) plays a crucial role in coordinating motor functions in the cortical and mesolimbic centres (Sperling & Müller, 2011). The LN neurons (Gp and P) are involved in various functions including visual attention, working memory, cognitive control, as well as the organisation and execution of movements. The volume of LN has been assessed due to intensive and intricate motor sequence learning (especially automatic movements) (Kowalczyk-Grębska et al., 2021).
The LN brain region is commonly associated with psychiatric disorders such as schizophrenia, addiction, anxiety, and depression. Currently, it seems that this

[1] Dokuz Eylul University Faculty of Medicine, Department of Anatomy, Izmir, Turkey.
ORCID iD: https://orcid.org/0000-0002-7467-0571, Email: funda.aksu@deu.edu.tr
[2] Dokuz Eylul University Faculty of Medicine, Department of Neurosurgery, Izmir, Turkey.
ORCID iD: https://orcid.org/0000-0002-8485-1421, Email: selim.karabekir@deu.edu.tr
[3] Dokuz Eylul University Faculty of Medicine, Department of Radiology, Dokuz Eylul University, Izmir, Turkey.
ORCID iD: https://orcid.org/0000-0002-1059-5517, Email: nurikarabay@gmail.com
[4] Manisa Celal Bayar University / Faculty of Sport Sciences, Manisa, Turkey.
ORCID iD: https://orcid.org/0000-0003-2199-9987, Email: erkanswim@gmail.com
*Correspondence: Assoc. Prof. Dr. Funda Aksu, Dokuz Eylül University Faculty of Medicine, Department of Anatomy, 35340 Inciralti, Izmir, Turkey. Email: funda.aksu@deu.edu.tr, Tel: +90 (232) 4124361

structure not only regulates motor functions, but also plays a more significant role than previously acknowledged in the management of psychiatric disorders. The investigation of the region's autonomous disease control function is a significant area of research (Hibar et al., 2013; Sperling & Müller, 2011).

While we encountered studies that conducted volumetric analyses of basal nuclei in our literature review, we were unable to find studies that specifically compared the proportional relationships between age, gender, BMI values, and LN and its subgroups (Gp and P). This study conducted volumetric analysis of lymph nodes (LN) using a semi-automatic tracings method with MRI. The analysis was performed on healthy subjects who exercised regularly, and the data was categorised by age and gender. A computer-based software programme was utilised for this purpose.

Material and methods

The study population comprised of physically active, healthy individuals aged 19-25 who were enrolled in Dokuz Eylül University Faculty of Medicine and engaged in regular exercise (3 times per week, approximately 2000 MET). The study included right-handed individuals who were in good health. A sample of sixteen individuals (7 female and 9 male) who were in good health was randomly selected for this study. Their MRI images of LN were analysed using a semi-automatic tracing technique. The study included participants who provided informed consent, which was obtained with the approval of the ethics committee.

MRI Scans and Image Processing

The study utilised T1-T2 weighted 3D gradient echo images (3D-TFE) obtained with an MRI device (Philips Ingenia 1.5T MRI system, Philips Medical Systems, Best, The Netherlands) for LN measurements in both study groups. Three-dimensional distorted gradient recalled echo sequence was used to acquire axial and coronal T1-weighted brain images. The study involved capturing cross-sections and sagittal pictures using SE T1A imaging technique in both sagittal and axial planes. No intravenous contrast enhancement or sedation was administered (Mas et al., 2009).

The images underwent analysis using the Easy Vision CT/MR software (Philips Medical Systems, Eindhoven, The Netherlands) after being submitted to a ViewForum postprocessing interface. This analysis involved tissue compartment segmentation and region of interest definition.

The preference for T1-weighted images is attributed to the enhanced contrast between grey and white matter. To reduce errors in manual tracing, the photos were magnified by a factor of four. The area of interest was identified through the integration of a thresholding technique, a region-growing algorithm for segmentation, and manual tracing using a mouse-guided cursor. The basal ganglia borders were manually delineated using axial plane pictures, with additional utilisation of sagittal and coronal plane images as needed for border determination.

The sagittal and axial MRI cross sections were analysed using a tracing technique to assess their volumes. The objective was to identify the plane that corresponds to the smallest diameter of the anisotropic structure. To minimise the margin of error, a consistent and sequential cross-section thickness of 0.3 cm was maintained. To minimise potential errors, the measurements and image acquisition were performed by the same operator. The clinical neuroradiologist thoroughly examined all images to rule out any significant pathology.

The cross-sections were assessed to determine the volumes of the left and right lentiform nuclei in relation to age, gender, and body mass index for each participant. The analysis was conducted using the semi-automatic tracking method in MRI (Figure 1).

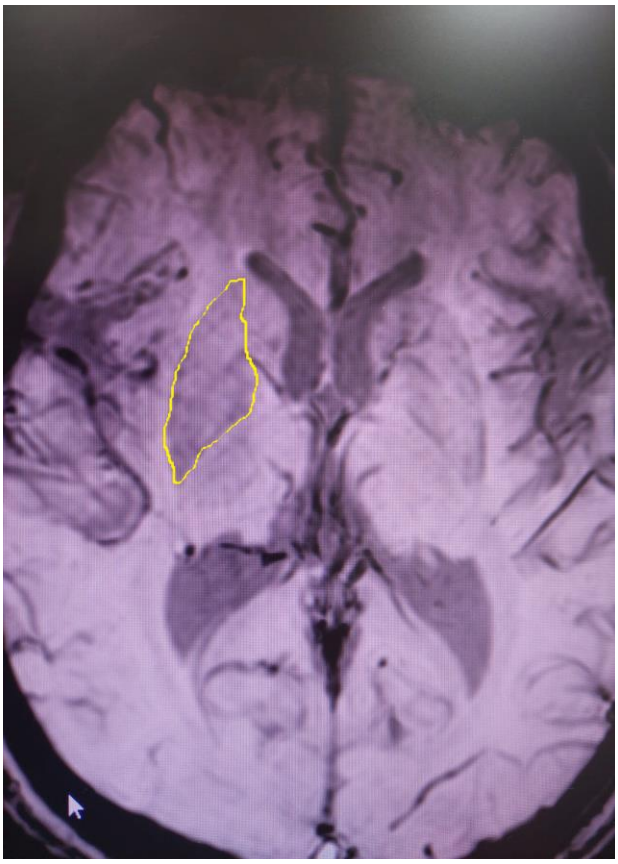

Figure 1. The Sample of Axial Mid-Cerebral Cross-Section Measurement of the Left LN (Putamen and Globus Pallidus) Using a Semi-Automatic Tracing Method on MRI.

Statistical Methods

Group variances were assessed for homogeneity using Levene's test. The normality of the continuous variable distribution was examined using the Shapiro-Wilk test. The variance-covariance matrices were examined for homogeneity using Box's M statistics. The study utilised dependent variables in a Repeated Measures Analysis of Variances (ANOVA) with two factors and repetition of one component to reduce error, as the parametric test assumptions were met. The independent groups t-test, also referred to as the student's t test, was employed for variables without repeated measurements and that met the assumptions of parametric tests. The Mann Whitney U test was used when a variable did not meet the assumptions of a parametric test. The Pearson and Spearman correlation coefficients were employed to evaluate the relationship between the variables. The results were expressed using the mean ± standard deviation (SD), median, and correlation coefficients. A significance level of $p < 0.05$ was considered statistically significant. The statistical software SPSS 26.0 (SPSS Ver. 26.0, SSPS Inc, Chicago IL, USA) was used for the analyses.

Results

The volumes of the right and left NL were statistically analysed in groups of healthy individuals who exercise regularly, with matching gender and age (Table 1). There was no statistically significant difference in the NL volume between men and women, although women had a slightly greater volume on both the right and left sides.

There was a higher volume of LN on the left side in right-left groups and genders, but the difference was not statistically significant (respectively p= 0.536; p=0.586); the putamen volume was higher on the left, but there was no significant difference (respectively p= 0.681; p=0.600); conversely, the GP volume was higher on the right, but there was no significant difference (p = 0.137; p=0.671) (Table 1).

There is no statistically significant difference in the total volume of the NL and its subgroups, GP and P, when comparing right-left and male-female groups (Table 1). The observed difference in right and left P volumes between men and women was not statistically significant (p=0.600).

Table 1

The Right and the Left Lentiform Nuclei (LN) Volume of Healthy Individuals Data in the Age and Gender-Matched Groups Were Recorded (mm^3).

		Right (mm^3)		p	Left (mm^3)		p
Nucleus lentiformis	Female (n=7)	6714.2	528.4		6739.9	689.3	
	Male (n=9)	6491.8	529.2	0.536	6539.5	729.0	0.586
	Total (n=16)	6589.1	523.5		6627.2	695.8	
Globus pallidus	Female (n=7)	1185.0	87.8		1132.6	95.9	
	Male (n=9)	1114.4	89.3	0.137	1112.2	91.0	0.671
	Total (n=16)	1145.3	93.0		1121.1	90.5	
Putamen	Female (n=7)	5529.2	447.9		5607.3	599.6	
	Male (n=9)	5377.4	530.7	0.681	5427.3	710.1	0.600
	Total (n=16)	5443.8	486.3		5506.0	649.0	

Correlations

A significant positive correlation was observed between the volume of the right GP and age in men (p = 0.032). A positive correlation was observed between the volume of the right P and BMI in men, although it did not reach statistical significance (p = 0.072). Women showed no significant correlation between the same parameters. A positive correlation was observed between left NL volume and BMI in all subjects, although it did not reach statistical significance (p = 0.070). When evaluated separately for women and men, we found no significant correlation between right and left LN volumes and other parameters. A correlation was observed between left P volume and BMI in all subjects; however, it did not reach statistical significance (p= 0.083).

Discussion

The literature does not provide any knowledge regarding the significance of comparative volumetric data for the LN in relation to age, gender, and BMI. Early research has shown that high-quality volumetric data gathered with advanced imaging methods like MRI is better and more useful for understanding brain structures in both healthy people and people with diseases. It's become more important to look at the volumetric differences in the LN anatomy in older people who have Parkinson's disease, strokes, striatonigral degeneration, multiple system atrophy, hemiballism-hemichorea with striatal hyperintensity cases, uremic encephalopathy, corticobasal degeneration, Alzheimer's disease, and other types of dementia because they are linked to getting older (Ekiz, 2020).

Both hemispheres of the brain exhibit functional and structural differences. Numerous studies have explored the impact of brain asymmetry in relation to gender, handedness, age, and genetic factors. Research has demonstrated that asymmetrical variations in subcortical structures are linked to diverse neuropsychiatric disorders. Abnormal asymmetries in the volume of the nucleus caudatus have been observed in children with developmental stuttering. Similarly, abnormal asymmetries in the volume of the globus pallidus have been observed in patients with attention deficit/hyperactivity disorder and schizophrenia (Ekiz, 2020).

Madan (2019) investigated the influence of age-related differences in brain structure on morphological measurements of subcortical structures. The researchers also examined the correlation between these measures and fractal dimensionality. The study employed two open-access MRI datasets, encompassing a sample size of more than 600 healthy adults across all age groups. The researchers demonstrated the reliability of shape-related measurements as indicators of ageing using a computational neuroanatomy framework.

Choy, Raine and Schug (2022) discovered that an enlarged striatum is a brain imaging correlate of psychopathy. Choy et al. (2022) found a positive correlation between higher levels of psychopathy and larger volumes in several subregions, including the caudate, putamen, nucleus accumbens, and globus pallidus. The study revealed that exercising individuals, regardless of gender, exhibit slightly higher volumes in the lentiform nuclei, putamen, and globus pallidus on the right side. Additionally, it was observed that women have slightly higher lentiform nuclei volumes compared to men. There is a lack of research in the literature regarding the volumetric differences of the nuclei lentiformis in relation to endocrine factors between male and female subjects (Van Hartesveldt & Joyce, 1986). Additional research is required to elucidate the volumetric disparities between genders by measuring oestrogen and testosterone levels.

Peterson et al. (1993) found that the volume of the left Gp is greater than that of the right Gp in right-handed individuals. The study revealed a higher volume of the Gp on the right side. However, there was no significant difference in Gp volume between genders. Additionally, a statistically significant positive correlation was observed between the volume of the right Gp and age specifically in men (p=0.032).

Ekiz (2020) reported that the right Gp volume is 1471.9±161.7 mm3 in women and 1611.1±119.0 mm3 in men. Similarly, the left Gp volume is 1447.4±157.7 mm3 in men and 1571.7±120.4 mm3 in women. They found that men's right and the left Gp volumes were larger than women's (Ekiz, 2020). In our study, the right Gp volume is 1185.0 87.8 mm^3 and 1114.4 89.3 mm^3 in women and men, respectively, and the left Gp volume is 1132.6 95.9 mm^3 and 1112.2 91.0 mm^3 in men and women, respectively. The authors used images of a total of 49 individuals between the ages of 20 and 40. In our study, images of 16 individuals aged between 19-25 were used. The difference in volumes in the two studies can be explained by the fact that volumes increase with increasing age. In our study, right and left Gp volumes in men were larger than in women but were not statistically significant.

Wyciszkiewicz and Pawlak (2014) determined the volume of the right Gp to be 1.739±0.20 cm3 and 1.842±0.24 cm3 in males and females, respectively. In addition, they found the volume to be 1.885±0.24 cm3 and 2.009±0.29 cm3 in females and males, respectively. Wyciszkiewicz and Pawlak (2014) observed a decrease in P and Gp volume with age. Additionally, they found that men have larger volumes of both right and left Gp compared to women. In our study, we found that the volumes of the right and left Gp were larger in men compared to women, although this difference was not statistically significant.

Ifthikharuddin et al. (2000) calculated the volume of the right Gp as 1.558±0.154 cm^3 and 1.591±0.144 cm3 in men and women, respectively, and the volume of the left Gp as 1.595±0.139 cm^3 and 1.630±0.100 cm^3 in men and women. The researchers reported that the left Gp volume was higher in women compared to men, but they found no significant difference in the volume of the right Gp between men and women (Ifthikharuddin et al., 2000). In our study, we found that the right Gp volume is 1185.0 87.8 mm^3 and 1114.4 89.3 mm^3 in women and men, respectively, and the left Gp volume is 1132.6 95.9 mm^3 and 1112.2 91.0 mm^3 in women and men, respectively. In our study, there was no statistically significant difference in the volumes of the right and left Gp between men and women.

According to Ekiz (2020), the right P volume was measured as 4056.0±328.5 mm3 in women and 4504.2±278.9 mm3 in men. The left P volume was found to be 4343.4±417.1 mm3 in women and 4817.5±380.0 mm3 in men. Ekiz (2020) found that men had larger right and left P volumes compared to women. The study revealed that the right P volume is 5529.2 ± 447.9 mm3 and 5377.4 ± 530.7 mm3 in women and men, respectively. Similarly, the left P volume is 5607.3 ± 599.6 mm3 and 5427.3 ± 710.1 mm3 in women and men, respectively. The results of our study are greater than those of the authors' study, possibly due to methodological differences in measurement. No significant difference was observed between genders in our study. However, the volume of the putamen was found to be higher on the left side, although this difference did not reach statistical significance.

Abedelahi et al. (2013) conducted a study on individuals under the age of 40, examining the volume of the right and left P. They found that in men, the volume of the right P was 5.35±0.71 cm3 and the volume of the left P was 5.19±0.68 cm3. In women, the volume of the right P was 5.63±0.92 cm3 and the volume of the left P was 5.46±0.88 cm3. Wyciszkiewicz and Pawlak (2014) determined that the volume of the right P was 6.138±0.68 cm3 in women and 6.641±0.77 cm3 in men. They also found that the volume of the left P was 6.393±0.73 cm3 in women and 6.869±0.80 cm3 in men.

Ifthikharuddin et al. (2000) reported the volume of the right P as 4.268±295 mm3 in women and 4,513±412 mm3 in men, and the volume of the left P as 4.195±343 mm3 in women and 4.452±410 mm3 in men. The studies found that the volumes of the right and left P regions were greater in men compared to women. Furthermore, some studies have found no significant difference in the P volume between men and women (Elkattan et al., 2017; Pitcher et al., 2012).

Elkattan et al. (2017) found a significant age-related decrease in P volume in both men and women. However, there was no significant difference in volume between the sexes. Several studies have reported a decrease in P volume with age (Koikkalainen et al., 2007; Walhovd et al., 2005; Walhovd et al., 2011). Another study found that the volumetric decrease due to age was greater in men compared to women (Brabec, Krásený, & Petrovický, 2003).

Although automated techniques offer potential bias reduction, the semi-automatic tracing method remains the preferred approach for demonstrating the orientation of the affected lymph node for surgical planning. You need to know a lot about deep brain anatomy, including the LN, to understand qualitative data from semi-automated studies that use MR imaging tracing methods. This study briefly discusses the clinical and surgical significance of using the semiautomatic volumetric measurement method for lymph node tracing. The utilisation of a semi-automatic tracing method to visualise neuroanatomical complex deep brain structures, such as P and Gp, in a 3-dimensional manner is highly beneficial in the field of neurosurgery for preoperative and intra/postoperative planning.

Andreasen et al. (1996) compared the volumes produced by "manuel traced" and "automatic" procedures. The study found that the results from the automatic atlas-based method of measuring regional brain volume were comparable to those from manual methods. The method is efficient, rapid, objective, and not affected by rater bias or poor interpreter reliability associated with the manual tracking technique. In a study conducted by Mas et al. (2009), they utilised a manual tracing semi-automatic method to assess human brain volume using the tracing technique. Their findings demonstrated that the measurements obtained through this method are considered the benchmark when compared to automatic measurements (Mas et al., 2009). Similarly, we utilised a semi-automated tracing method to ensure an objective and efficient approach in defining the boundaries of the structure for accurate volume measurements. Additionally, we utilised a combined approach to visually identify the boundaries of the structure that the radiologist will measure in terms of volume.

Conclussion

The study's findings indicate that there are slight differences in the volumes of the lentiform nuclei, putamen, and globus pallidus between exercising individuals, regardless of gender. Additionally, it was observed that women tend to have slightly higher lentiform nuclei volumes compared to men, suggesting gender differences. Further research is required to delve into the potential impact of exercise capacity on these variations. It is expected that the semi-automatic tracing technique employed could prove to be a valuable approach for assessing brain regions and studying changes in volume associated with cognitive abilities and exercise.

For future research, it would be valuable to conduct a comparative examination of P and Gp volumes and interconnected brain regions, including the nucleus caudatus, substantia nigra, prefrontal cortex, and thalamus. This evaluation should consider factors such as age, gender, and BMI. To enhance the validity of future large series case control studies on LN pathologies, it will be crucial to establish correlations with functional imaging modalities and compare the findings with our existing data. The findings in this study offer a valuable contribution to the LN morphology of healthy individuals and may hold significance for clinicians and surgeons.

There are some limitations on our study. The size of our sample was relatively small. The limited number of participants was a result of the exclusive demographic that engages in regular exercise. In addition, certain structures within the basal ganglia, including the subthalamic nucleus, nucleus accumbens, caudate nucleus, and substantia nigra, were not included in the analysis due to their limited dimensions and low image quality observed on MRI scans.

Acknowledgments

We are grateful to Dr. Nuket Gocmen Karabekir (Department of Anatomy) for helping with collection of imaging files and Dr. Ayse Canan Yazıcı (Department of Biostatistics) for statistical analyze.

Funding Information

This research received no external funding.

References

Abedelahi, A., Hasanzadeh, H., Hadizadeh, H., & Joghataie, M. T. (2013). Morphometric and volumetric study of caudate and putamen nuclei in normal individuals by MRI: Effect of normal aging, gender and hemispheric differences. *Polish Journal of Radiology, 78*(3), 7-14. https://doi.org/10.12659/pjr.889364

Andreasen, N. C., Rajarethinam, R., Cizadlo, T., Arndt, S., Swayze, V. W., Flashman, L. A., O'leary, D. S., Ehrhardt, J. C., & Yuh, W. T. (1996). Automatic Atlas-Based Volume Estimation of Human Brain Regions from MR Images. *Journal of Computer Assisted Tomography, 20*(1), 98-106. https://doi.org/10.1097/00004728-199601000-00018

Brabec, J., Krásený, J., & Petrovický, P. (2003). Volumetry of striatum and pallidum in man--anatomy, cytoarchitecture, connections, MRI and aging. *Sbornik lekarsky, 104*(1), 13-65. https://europepmc.org/article/med/14577136

Choy, O., Raine, A., & Schug, R. (2022). Larger striatal volume is associated with increased adult psychopathy. *Journal of Psychiatric Research, 149*, 185-193. https://doi.org/10.1016/j.jpsychires.2022.03.006

Ekiz, Y. (2020). *Ratio of the volume of the basal nuclei to the whole brain in individuals aged 20-40 and their right-left comparison* [Doctoral Thesis, Istanbul Medipol University]. https://hdl.handle.net/20.500.12511/8360

Elkattan, A., Mahdy, A., Eltomey, M., & Ismail, R. (2017). A Study of volumetric variations of basal nuclei in the normal human brain by magnetic resonance imaging. *Clinical Anatomy, 30*(2), 175-182. https://doi.org/10.1002/ca.22813

Hänggi, J., Langer, N., Lutz, K., Birrer, K., Mérillat, S., & Jäncke, L. (2015). Structural brain correlates associated with professional handball playing. *PLoS One, 10*(4), e0124222. https://doi.org/10.1371/journal.pone.0124222

Hibar, D. P., Stein, J. L., Ryles, A. B., Kohannim, O., Jahanshad, N., Medland, S. E., Hansell, N. K., McMahon, K. L., de Zubicaray, G. I., Montgomery, G. W., Martin, N. G., Wright, M. J., Saykin, A. J., Jack, C. R., Weiner, M. W., Toga, A. W., Thompson, P. M., & the Alzheimer's Disease Neuroimaging, I. (2013). Genome-wide association identifies genetic variants associated with lentiform nucleus volume in N = 1345 young and elderly subjects. *Brain Imaging and Behavior, 7*(2), 102-115. https://doi.org/10.1007/s11682-012-9199-7

Ifthikharuddin, S. F., Shrier, D. A., Numaguchi, Y., Tang, X., Ning, R., Shibata, D. K., & Kurlan, R. (2000). MR volumetric analysis of the human basal ganglia: normative data. *Academic Radiology, 7*(8), 627-634. https://doi.org/10.1016/S1076-6332(00)80579-6

Koikkalainen, J., Hirvonen, J., Nyman, M., Lötjönen, J., Hietala, J., & Ruotsalainen, U. (2007). Shape variability of the human striatum—effects of age and gender. *Neuroimage, 34*(1), 85-93. https://doi.org/10.1016/j.neuroimage.2006.08.039

Kowalczyk-Grębska, N., Skorko, M., Dobrowolski, P., Kossowski, B., Myśliwiec, M., Hryniewicz, N., Gaca, M., Marchewka, A., Kossut, M., & Brzezicka, A. (2021). Lenticular nucleus volume predicts performance in real-time strategy game: cross-sectional and training approach using voxel-based morphometry. *Annals of the New York Academy of Sciences, 1492*(1), 42-57. https://doi.org/10.1111/nyas.14548

Madan, C. R. (2019). Shape-related characteristics of age-related differences in subcortical structures. *Aging & Mental Health, 23*(7), 800-810. https://doi.org/10.1080/13607863.2017.1421613

Mas, N., Senan, S., Firat, M., Tuncel, M., & Basar, R. (2009). Evaluation of human brain volume by the tracing technique. *Neurosciences Journal, 14*(1), 96-97. https://nsj.org.sa/content/14/1/96.short

Park, I. S., Lee, K. J., Han, J. W., Lee, N. J., Lee, W. T., Park, K. A., & Rhyu, I. J. (2009). Experience-Dependent Plasticity of Cerebellar Vermis in Basketball Players. *The Cerebellum, 8*(3), 334-339. https://doi.org/10.1007/s12311-009-0100-1

Peterson, B. S., Riddle, M. A., Cohen, D. J., Katz, L. D., Smith, J. C., & Leckman, J. F. (1993). Human basal ganglia volume asymmetries on magnetic resonance images. *Magnetic Resonance Imaging, 11*(4), 493-498. https://doi.org/10.1016/0730-725X(93)90468-S

Pitcher, T. L., Melzer, T. R., MacAskill, M. R., Graham, C. F., Livingston, L., Keenan, R. J., Watts, R., Dalrymple-Alford, J. C., & Anderson, T. J. (2012). Reduced striatal volumes in Parkinson's disease: a magnetic resonance imaging study. *Translational Neurodegeneration, 1*(1), 17. https://doi.org/10.1186/2047-9158-1-17

Saunders, A., Huang, K. W., & Sabatini, B. L. (2016). Globus Pallidus Externus Neurons Expressing parvalbumin Interconnect the Subthalamic Nucleus and Striatal Interneurons. *PloS One, 11*(2), e0149798. https://doi.org/10.1371/journal.pone.0149798

Sperling, W., & Müller, H. (2011). Nucleus lentiformis–A new model for psychiatry? *Medical Hypotheses, 76*(5), 720-722. https://doi.org/10.1016/j.mehy.2011.02.005

Standring, S., Ellis, H., Healy, J., Johnson, D., Williams, A., Collins, P., & Wigley, C. (2005). Gray's Anatomy, 39th Edition: The Anatomical Basis of Clinical Practice. *American Journal of Neuroradiology, 26*(10), 2703-2704. https://www.ajnr.org/content/26/10/2703/tab-article-info

Van Hartesveldt, C., & Joyce, J. N. (1986). Effects of estrogen on the basal ganglia. *Neuroscience & Biobehavioral Reviews, 10*(1), 1-14. https://doi.org/10.1016/0149-7634(86)90029-1

Walhovd, K. B., Fjell, A. M., Reinvang, I., Lundervold, A., Dale, A. M., Eilertsen, D. E., Quinn, B. T., Salat, D., Makris, N., & Fischl, B. (2005). Effects of age on volumes of cortex, white matter and subcortical structures. *Neurobiology of Aging, 26*(9), 1261-1270. https://doi.org/10.1016/j.neurobiolaging.2005.05.020

Walhovd, K. B., Westlye, L. T., Amlien, I., Espeseth, T., Reinvang, I., Raz, N., Agartz, I., Salat, D. H., Greve, D. N., & Fischl, B. (2011). Consistent neuroanatomical age-related volume differences across multiple samples. *Neurobiology of Aging, 32*(5), 916-932. https://doi.org/10.1016/j.neurobiolaging.2009.05.013

Wyciszkiewicz, A., & Pawlak, M. A. (2014). Basal ganglia volumes: MR-derived reference ranges and lateralization indices for children and young adults. *The Neuroradiology Journal, 27*(5), 595-612. https://doi.org/10.15274/NRJ-2014-10073