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ORIGINAL ARTICLE

Medicine Science International Medical Journal

Medicine Science 2026;15(2):948-54

Does non-arteritic anterior ischemic optic neuropathy affect the volumes of limbic system structures?

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Received 11 December 2025; Accepted 23 January 2026
Available online 30 May 2026 with doi: 10.5455/medscience.2025.12.347

Abstract

In this study, we aimed to comprehensively examine the effect of non-arteritic anterior ischemic optic neuropathy (NAION) on limbic system structures using the volBrain automated segmentation method. Among 22 patients diagnosed with NAION, 14 (9 males, 5 females) with Magnetic Resonance Images (MRI) were included in the study. The control group consisted of 14 healthy individuals of the same age and gender who underwent MRI for any reason. The mean age in both groups was 62.5 ± 9.49 years. Volumetric analysis of limbic system structures was performed on the images using the VolBrain system. Right amygdala volume (0.94 ± 0.12 cm^3 vs. 1.06 ± 0.10 cm^3, p=0.011), left amygdala volume (0.93 ± 0.09 cm^3 vs. 1.01 ± 0.10 cm^3, p=0.034), total amygdala volume (1.87 ± 0.20 cm^3 vs. 2.06 ± 0.19 cm^3, p=0.016), left CA4-DG volume (0.30 ± 0.07 cm^3 vs. 0.38 ± 0.08 cm^3, p=0.008), and total CA4-DG volume (0.62 ± 0.13 cm^3 vs. 0.70 ± 0.06 cm^3, p=0.031) were significantly lower in the NAION group compared to healthy controls. Based on our results, we suggest that the reduction in visual input in NAION patients may be associated with changes in certain limbic system structures involved in learning, memory, and habit-forming functions.

Keywords: Limbic system, non-arteritic anterior ischemic optic neuropathy, volumetric analysis

Introduction

Optic neuropathy (ON) is a clinical condition that affects visual acuity and color vision and may also causes visual field defect. ON can occur due to trauma, radiation, inflammation, compression, toxicities, ischemia, or tumors involving the optic nerve or its sheath. It may also occur due to diseases such as multiple sclerosis and Graves disease [1,2]. Non-arteritic anterior ischemic ON (NAION) is the most common type of acute ON in patients over the age of 50. It causes acute, painless, unilateral vision loss [3,4]. The pathogenesis of NAION is unclear. It is thought to be caused by local arteriosclerosis, embolization, diffuse hypoperfusion, vasospasm, obstruction of the venous system or a combination of these mechanisms has been proposed [4]. The structures that make up the limbic system are located close to the inner wall of the cerebral hemispheres and have functions related to emotion and memory [5,6]. The limbic system consists of many structures such as the hippocampus, amygdala, cingulate and parahippocampal gyrus, prefrontal cortex, rhinencephalon, cingulum, hypothalamus, and connections between these structures [6]. While the formation and perception of emotions are provided by the cingulate gyrus and orbitofrontal cortex, their expression is carried out by the hippocampal formation, hypothalamus and amygdala [5]. Studies in the literature investigating the volumetric effects of vision loss on cortical visual areas and the limbic system have shown that in diseases affecting vision, there are volumetric changes in various regions of the brain, especially the visual cortex, and that morphometric effects are even related to the duration of blindness

CITATION
Urhan AT, Cakir RN, Kaya Celik E, et al. Does non-arteritic anterior ischemic optic neuropathy affect the volumes of limbic system structures?. Med Science. 2026;15(2):948-54.

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DOI: 10.5455/medscience.2025.12.347

[7-9]. Magnetic resonance (MR) imaging is the preferred method for diagnosing central nervous system diseases. It is highly useful in the differential diagnosis and prognosis of ON. Studies that automatically calculate potential changes in brain volume in various clinical situations are becoming increasingly common [7,8,10]. While there is one study in the literature examining the effects of isolated optic neuritis on the amygdala, hippocampus, and caudate nucleus volumes [10], To our knowledge, no previous studies have been comprehensively reviewed. Based on previous evidence indicating that visual deprivation may influence limbic system plasticity, we hypothesized that NAION-related reduction in visual input could be associated with volumetric alterations in specific limbic subregions, particularly those involved in emotional processing and memory functions, such as the amygdala and hippocampal subfields. Therefore, in this study, we aimed to comprehensively examine the effects of NAION on limbic system structures using the volBrain automatic segmentation method.

Material and Methods

Before starting our study, approval was obtained from the Tokat Gaziosmanpaşa University Faculty of Medicine Clinical Research Ethics Committee (No: 83116987-696, Date: 23 November 2023). Based on a two-sided hypothesis, each group was required to have 13 individuals, considering a 95% confidence level (1-α) and a 95% test power (1-β) with an effect size of d=1.493 [9]. Magnetic Resonance Images (MRI) obtained from the Sectra archive system of the Department of Radiology of Tokat Gaziosmanpaşa University Hospital were used. Patients who were diagnosed with NAION based on comprehensive clinical and ophthalmological evaluations performed by an experienced ophthalmologist were eligible for inclusion in the study. Of the 22 patients diagnosed with NAION between 2019 and 2024, 14 patients (9 males and 5 females) who had available brain MRI data were ultimately included in the final analysis. Eight of these patients had left eye involvement, six had right eye involvement. The control group consisted of fourteen age- and sex-matched healthy individuals (9 males and 5 females) who presented with non-specific complaints such as headache or dizziness, underwent brain MRI with no detected pathology, and had no history or evidence of neurological disorders that could potentially influence volumetric measurements of the limbic system. Brain imaging data for all participants were obtained at Tokat Gaziosmanpaşa University Faculty of Medicine Hospital using a Philips Medical Systems 3.0 T Gyroscan NT device. T1-weighted, three-dimensional, high-resolution sagittal plane images were acquired with a 1 mm^3 isovoxel size, TR=8.1 ms, TE=3.7 ms, TFE=230 ms, flip angle=8°, 224×224 pixel matrix size, and 224×224 mm FOV. All images were recorded in DICOM format and anonymized prior to evaluation. Brain MRI were processed and volumetric analyses were performed using the free online platform VolBrain (v.1.0, http://volbrain.upv.es). VolBrain offers a fully automated segmentation process based on multi-atlas patch-based label fusion segmentation technology [11]. The images acquired from T1-weighted three-dimensional volumetric turbo field echo (TFE) sequences acquired by MRI devices were uploaded to this system. The raw MRI were converted to Niftii format to use the VolBrain system. During this conversion process, MRI downloaded from the Sectra archive system were processed in DICOM format using the RadiAnt program. The DICOM images were converted to Niftii format using the dcm2niigui tab of the Mricron program. Then, in the VolBrain system on the website, the MR image converted to Niftii format was entered into the HIPS module and the limbic system was parcellated. In addition, the visual data obtained from the VolBrain system were converted into three-dimensional models with a program called ITK-SNAP (Figure 1 and Figure 2).

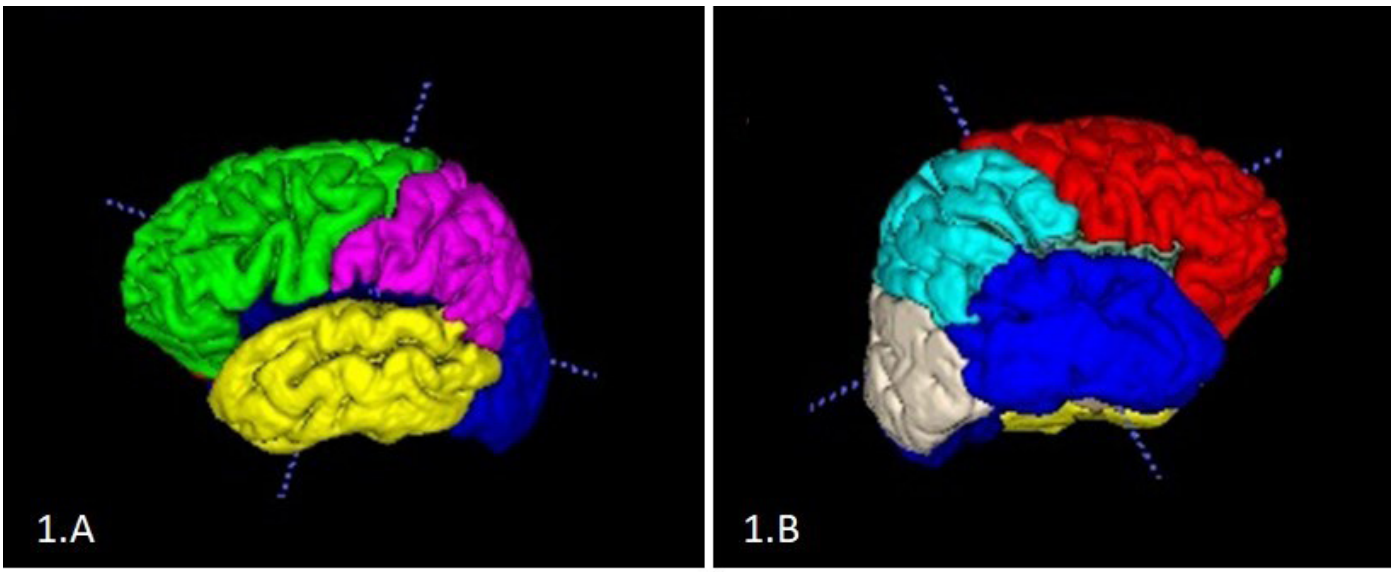

Figure 1. 3D segmentation images generated by ITK-SNAP of a 53-year-old patient diagnosed with NAİON. 1A and B. Brain segmentation

DOI: 10.5455/medscience.2025.12.347

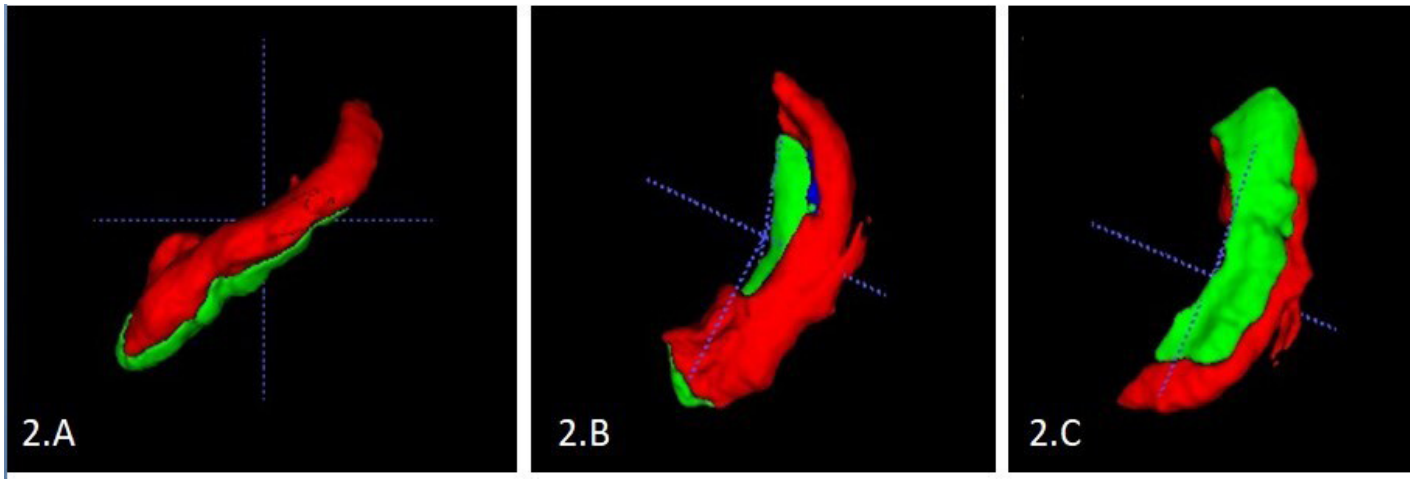

Figure 2. 3D segmentation images generated by ITK-SNAP of a 53-year-old patient diagnosed with NAİON. 2A, B, and C. Hippocampus segmentation

Although the VolBrain platform provides automated intracranial volume (ICV) estimates, volumetric comparisons in the present study were performed using raw volume values. Given the strict age- and sex-matching between groups, this approach was deemed appropriate; however, the lack of ICV normalization should be considered when interpreting the results.

Statistical Analysis

SPSS 26 software (SPSS Inc., Chicago, Illinois, USA) was used to evaluate the data. The distribution characteristics of the data were assessed using the Shapiro–Wilk test. The Independent Samples t-test was applied to compare the groups, as the parametric assumptions of the data were met. A p-value of <0.05 was considered statistically significant.

Results

The mean age in both groups was 62.5 ± 9.49 years. The medical histories of the patients in the The NAION group included one patient with trauma, one with alcohol intoxication, one with a history of frontal lobe surgery, two with diabetes mellitus (DM), two with coexisting DM and hypertension (HT), two with optic atrophy, and five with glaucoma. While the right and total subiculum volumes were higher in the NAION group than in the control group, all other subcortical structure volumes were higher in the control group. The reductions in right amygdala volume (p=0.011), left amygdala volume (p=0.034), total amygdala volume (p=0.016), left CA4-DG volume (p=0.008), and total CA4-DG volume (p=0.031) in the NAION group compared to the control group were statistically significant. The results are presented in Table 1, Figure 3 and Figure 4. Effect size analysis of the limbic structures that showed statistically significant group differences revealed that all parameters had large Cohen's d values (Table 2).

Figure 3. Comparison of mean volumes of the amygdala, caudate nucleus, and thalamus between the NAION and control groups

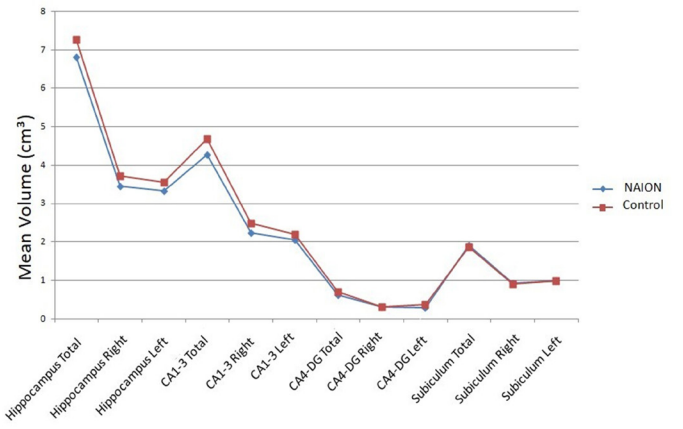

Figure 4. Comparison of mean volumes of the hippocampus, CA1-3, CA4-DG subregions and subiculum between the NAION and control groups

DOI: 10.5455/medscience.2025.12.347

Table 1. Comparison of mean volume values between the NAION and control groups

Volume (cm^3)	NAION Mean ± SD	Control Mean ± SD	p
Amygdala total	1.87 ± 0.20	2.06 ± 0.19	**0.016**
Amygdala right	0.94 ± 0.12	1.06 ± 0.10	**0.011**
Amygdala left	0.93 ± 0.09	1.01 ± 0.10	**0.034**
Caudate nucleus total	5.40 ± 0.73	5.79 ± 0.40	0.090
Caudate nucleus right	2.73 ± 0.36	2.95 ± 0.21	0.057
Caudate nucleus left	2.67 ± 0.38	2.85 ± 0.23	0.158
Thalamus total	14.37 ± 1.41	14.97 ± 1.12	0.223
Thalamus right	7.16 ± 0.70	7.45 ± 0.56	0.225
Thalamus left	7.21 ± 0.75	7.51 ± 0.57	0.233
Hippocampus total	6.81 ± 0.81	7.27 ± 0.92	0.173
Hippocampus right	3.46 ± 0.44	3.71 ± 0.54	0.190
Hippocampus left	3.32 ± 0.38	3.56 ± 0.40	0.123
CA1-3 total	4.28 ± 0.49	4.69 ± 0.91	0.156
CA1-3 right	2.24 ± 0.29	2.49 ± 0.72	0.231
CA1-3 left	2.05 ± 0.21	2.20 ± 0.26	0.102
CA4-DG total	0.62 ± 0.13	0.70 ± 0.06	**0.031**
CA4-DG right	0.32 ± 0.08	0.32 ± 0.07	0.873
CA4-DG left	0.30 ± 0.07	0.38 ± 0.08	**0.008**
Subiculum total	1.91 ± 0.27	1.87 ± 0.28	0.729
Subiculum right	0.93 ± 0.12	0.90 ± 0.25	0.637
Subiculum left	0.98 ± 0.16	0.98 ± 0.13	1.000

NAION: Non-arteritic anterior ischemic optic neuropathy group. Independent Samples Testi p-value of <0.05 was considered statistically significant

Table 2. Effect size (Cohen's d) values for limbic structures showing statistically significant group differences between NAION and control groups

Structure	Cohen's d	Effect size interpretation
CA4-DG total	0.86	Large
CA4-DG left	1.08	Large
Amygdala total	0.98	Large
Amygdala right	1.03	Large
Amygdala left	0.85	Large

Cohen's d values were interpreted as small (0.2), medium (0.5), and large (≥0.8). All reported parameters demonstrated large effect sizes, indicating clinically meaningful volumetric differences despite the relatively small sample size

DOI: 10.5455/medscience.2025.12.347

Discussion

This study is one of the first volumetric MRI investigations to evaluate limbic system volumes in patients with NAION. Our findings suggest that damage to the visual pathway may also have effects on brain regions involved in emotional and behavioral functions.

In a study in the literature, MRI of 138 healthy adult individuals (72 females and 66 males) were evaluated volumetrically by Özen et al. [12] to determine the volumes of the hippocampus and its subfields, and found that the total hippocampus volume was higher in men (7.47 cm3) than in women (6.67 cm3). It was also observed that the volumes of CA1-3, CA4-DG, and subiculum were larger in men than in women. It has been reported that the volumes of the hippocampus and CA1-3 subregions are greater on the right side than on the left. However, it has been reported that the volumes of the CA4-DG subregions are equal on the right and left sides, while the volume of the subiculum is greater on the left side than on the right. Although we evaluated fewer individuals in our study and were unable to make comparisons between men and women, we obtained data that was quite consistent with the results of Özen et al. [12] in terms of the volumes of the hippocampus and its subregions in 14 healthy individuals.

In the literature, there are various studies examining visual cortical areas in individuals with vision loss. In diseases leading to vision loss, morphometric changes are observed in various parts of the brain, mainly in the visual areas [7-9]. It was observed that blind people developed alternative strategies to locate objects in the environment using their other senses [13]. Studies have shown that visually impaired individuals can enhance their auditory capacities, such as sound discrimination, speech identification, and auditory spatial localization, by sharpening their attention [14-16]. It has been reported that blindness causes changes not only in the visual pathways and centers but also in the limbic system structures [17,18]. It has been shown that early and late blind individuals have increased volume in the hippocampus, regardless of the duration of blindness, and also have superior navigation skills compared to sighted individuals [18]. In an experimental study examining the effects of early blindness both with MRI and histopathologically, Touj et al. demonstrated a volume decrease in visual cortical areas, but an increase in volume in the amygdala and piriform cortex [17].

Navigational changes in hippocampal volume and activity have been observed during visual deprivation. It has been reported that functional connectivity in the hippocampus increases when visual stimuli are absent, and this may be related to increased load on hippocampal networks. Furthermore, the observation of these changes in both early and late blindness suggests experience-dependent rather than developmental-dependent plasticity in the hippocampal intrinsic functional network [19].

In the literature, bilateral decrease in hippocampus volume has been reported in patients with advanced glaucoma [9]. Another study reported a decrease in volumes of both the occipital cortex and visual pathways, as well as the hippocampus, in Charles Bonnet Syndrome, which affects the eye, visual pathways, or visual cortex. A negative correlation between the severity of visual hallucinations and hippocampal volume has been identified in these patients. It has been reported that cognitive decline and impaired insight experienced in both neurodegenerative diseases and vision loss may be related to changes in hippocampal volume [8].

In a volumetric study evaluating MRI of 16 patients with isolated optic neuritis, volume reduction was observed in the CA1-4 regions of the hippocampal areas [10].

Maller et al. [7] reported a decrease in volume and thickness in the visual areas of the brains of blind individuals, but no difference in hippocampal volume between sighted and blind groups.

The limbic system is a complex structure involved in psychosocial development and the emergence of individual characteristics, playing a role in various functions such as emotional state, appropriate behavior, memory, and reasoning [20]. The hippocampus plays a role in episodic, relational, and spatial memory, while the caudate nucleus plays a role in procedural learning and the automation of behavior or habit formation. These two systems are generally shown to operate independently of each other. The amygdala, on the other hand, is an important center for processing emotions [21,22]. Previous neuroimaging studies comparing individuals with visual impairment to healthy controls have demonstrated that structural brain changes associated with visual loss are not limited to the visual cortex but may also involve limbic system structures, including the amygdala. In patients with advanced glaucoma, which represents a chronic form of visual deprivation, volumetric MRI analyses have revealed significant reductions in subcortical gray matter volumes, including the amygdala, compared to healthy individuals [9]. Similarly, studies investigating sensory deprivation and vision-related neurological conditions have suggested that reduced afferent sensory input may lead to experience-dependent plastic changes in limbic regions involved in emotional processing and behavioral regulation [17]. In line with these observations, the present study demonstrated significantly lower right, left, and total amygdala volumes in patients with NAION compared to age- and sex-matched controls.

An MRI study investigating the effect of psychosocial factors on hippocampal subfields in middle-aged and older individuals found that childhood maltreatment was associated with lower volumes of the total hippocampus and all subfields except CA3. In contrast, individuals who had recently experienced a stressful event were found to have higher volumes of the total hippocampus and all subfields. Additionally, low social support was associated with lower CA3 volume [23].

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In our study, the volumes of limbic system structures, except for the subiculum, were lower in the NAION group than in the control group. The decrease in total, right, and left amygdala volumes and total and left CA4-DG volume values was statistically significant.

Since there are conflicting data in the literature regarding the increase [17,18], decrease [9,10] or no change [7] in the hippocampus volume in diseases affecting vision, Zakani et al. [24] conducted a study to investigate the mechanism of the hippocampus's effect. They examined the brain MRI of patients with neuromyelitis optica spectrum disorders, including optic neuritis, and also examined the tissue samples they obtained pathologically. In the same study, they also created an experimental animal model and evaluated the hippocampus immunohistochemically. They reported that astrocyte damage, microglial activation, and neuronal damage reduced hippocampal volume. Retrograde neuronal degeneration affecting different axonal pathways and neuronal networks was observed in tissue samples taken from a patient with widespread destructive lesions in the optic nerves or spinal cord and hippocampal volume loss detected on MRI.

Still, it is not clear whether distant lesions and related retrograde neuronal degeneration alone cause extensive volume loss in the hippocampus or whether they act in conjunction with small astrocytic-destructive and microglia-activating lesions that may be overlooked in MR imaging due to the small size of the hippocampus or the inadequacy of the time interval selected for examination.

Although the majority of limbic system structures demonstrated lower mean volumes in the NAION group, the subiculum exhibited a non-significant trend toward higher mean volume. The subiculum represents one of the most anatomically complex hippocampal subregions, characterized by extremely thin and gradual transitional boundaries with adjacent CA subfields. Previous methodological studies have emphasized that automated atlas-based segmentation approaches may estimate these borders rather than delineate them with absolute anatomical precision, particularly in small subfields with limited contrast resolution on conventional MRI [11,25]. Consequently, volumetric measurements of the subiculum are known to be especially sensitive to image quality, segmentation algorithms, and minor variations in atlas registration. In addition, small sample size–related variability may further amplify such opposite-direction trends in subregional analyses.

We acknowledge that this study has several limitations. First, the sample size was relatively small, reflecting both the rarity of NAION and the constraints of retrospective MRI data availability. Although we included all eligible patients within our institutional archive, the limited cohort size may reduce statistical power and restrict the generalizability of our findings. We also consider the inability to perform laterality-based or correlation analyses due to sample size limitations as a methodological limitation. Additionally, patients could not be stratified based on systemic comorbidities (e.g., glaucoma, diabetes mellitus, hypertension, optic atrophy), which are known to influence vascular and neurodegenerative processes. Another limitation of the current study is the lack of previously published studies directly examining the relationship between NAION and volumetric measurements of limbic system parameters; this has limited the scope of direct comparisons with the existing literature. Future multicenter prospective studies with larger and clinically stratified cohorts are warranted to validate our results and further elucidate the central neural alterations associated with NAION. Despite these limitations, the present study provides valuable preliminary evidence and methodological insight for subsequent research exploring central nervous system involvement in this rare neuro-ophthalmic condition.

Conclusion

In conclusion, this study provides preliminary evidence that NAION may be associated with structural alterations beyond the visual pathways, potentially involving limbic system structures implicated in emotional and behavioral regulation. Despite the modest sample size, our findings highlight the importance of considering central nervous system involvement in NAION and offer a methodological foundation for future neuroimaging investigations. Multicenter research with larger populations and comprehensive clinical profiling will be essential to further elucidate the neurobiological mechanisms underlying this condition.

Ethical Approval
Approved by the Tokat Gaziosmanpaşa University Faculty of Medicine Clinical Research Ethics Committee (No: 83116987-696, Date: 23 November 2023).

Patient Consent
Informed consent was waived due to the retrospective design.

Conflict of Interest
The authors declare no conflict of interest.

Funding
The authors received no financial support for this study.

References

1. Tantiwongkosi B, Mafee MF. Imaging of optic neuropathy and chiasmal syndromes. Neuroimaging Clin N Am. 2015;25:395-410.
2. Poonam NS, Alam MS, Oberoi P, Mukherjee B. Dysthyroid optic neuropathy: Demographics, risk factors, investigations, and management outcomes. Indian J Ophthalmol. 2022;70:4419-26.
3. Hattenhauer MG, Leavitt JA, Hodge DO, et al. Incidence of nonarteritic anterior ischemic optic neuropathy. Am J Ophthalmol. 1997;123:103-7.
4. Levin LA, Danesh-Meyer HV. Hypothesis: a venous etiology for nonarteritic anterior ischemic optic neuropathy. Arch Ophthalmol. 2008;126:1582-5.
5. Hall JE. Guyton and Hall Textbook of Medical Physiology. Elsevier Health Sciences; 2016.
6. Standring S, Ellis H, Healy J, et al. Gray's Anatomy. Elsevier; 2008.

7. Maller JJ, Thomson RH, Ng A, et al. Brain morphometry in blind and sighted subjects. J Clin Neurosci. 2016;33:89-95.

8. Firbank MJ, daSilva Morgan K, Collerton D, et al. Investigation of structural brain changes in Charles Bonnet syndrome. Neuroimage Clin. 2022;35:103041.

9. Frezzotti P, Giorgio A, Motolese I, et al. Structural and functional brain changes beyond visual system in patients with advanced glaucoma. PLoS One. 2014;9:e105931.

10. Sayin Sakul A, Pençe KB, Ormeci T, Gunal M. Can volumetric analysis of the brain help diagnose isolated optic neuritis?. Clin Anat. 2023;36:1109-15.

11. Coupé P, Manjón JV, Fonov V, et al. Patch-based segmentation using expert priors: Application to hippocampus and ventricle segmentation. Neuroimage. 2011;54:940-54.

12. Özen KE, Coşkun Sağlam Ö, Kibar Karagöz C, et al. Morphometric evaluation of the human hippocampus and hippocampal subfield volume characteristics by VolBrain/HIPS. Anat Sci Int. 2025:1-14.

13. Loomis JM, Klatzky RL, Golledge RG. Navigating without vision: basic and applied research. Optom Vis Sci. 2001;78:282-9.

14. Liotti M, Ryder K, Woldorff MG. Auditory attention in the congenitally blind: where, when and what gets reorganized? Neuroreport. 1998;9:1007-12.

15. Hugdahl K, Ek M, Takio F, et al. Blind individuals show enhanced perceptual and attentional sensitivity for identification of speech sounds. Cogn Brain Res. 2004;19:28-32.

16. RoÈder B, Teder-SaÈlejaÈrvi W, Sterr A, et al. Improved auditory spatial tuning in blind humans. Nature. 1999;400:162-6.

17. Touj S, Gallino D, Chakravarty MM, et al. Structural brain plasticity induced by early blindness. Eur J Neurosci. 2021;53:778-95.

18. Fortin M, Voss P, Lord C, et al. Wayfinding in the blind: larger hippocampal volume and supranormal spatial navigation. Brain. 2008;131:2995-3005.

19. Ma G, Yang D, Qin W, et al. Enhanced functional coupling of hippocampal sub-regions in congenitally and late blind subjects. Front Neurosci. 2017;10:612.

20. Heimer L, Van Hoesen GW. The limbic lobe and its output channels: implications for emotional functions and adaptive behavior. Neurosci Biobehav Rev. 2006;30:126-47.

21. Bohbot VD, Iaria G, Petrides M. Hippocampal function and spatial memory: evidence from functional neuroimaging in healthy participants and performance of patients with medial temporal lobe resections. Neuropsychology. 2004;18:418.

22. Mizumori SJ, Yeshenko O, Gill KM, Davis DM. Parallel processing across neural systems: implications for a multiple memory system hypothesis. Neurobiol Learn Mem. 2004;82:278-98.

23. Twait EL, Blom K, Koek HL, et al. Psychosocial factors and hippocampal subfields: The Medea-7T study. Hum Brain Mapp. 2023;44:1964-84.

24. Zakani M, Nigritinou M, Ponleitner M, et al. Paths to hippocampal damage in neuromyelitis optica spectrum disorders. Neuropathol Appl Neurobiol. 2023;49:e12893.

25. Iglesias JE, Augustinack JC, Nguyen K, et al. A computational atlas of the hippocampal formation using ex vivo, ultra-high resolution MRI: Application to adaptive segmentation of in vivo MRI. Neuroimage. 2015;115:117-37.