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RESEARCH

A neuroimaging study of altered cortical and subcortical volume in adolescent methamphetamine users

Metamfetamin kullanan ergenlerin kortikal ve subkortikal beyin hacim değişimlerinin nörogörüntüleme çalışması

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Abstract

Purpose: The aim of this study was is to compare brain structure volume, including cortical and subcortical regions of adolescents- methamphetamine users versus non-users.

Materials and Methods: The study was designed to be cross-sectional, and structural magnetic resonance imaging scans were obtained from the participants, including ten methamphetamine users and nine non-users. volBrain program was used to evaluate the images.

Results: The results showed that methamphetamine users altered brain structures- temporal, parietal lobes, nucleus accumbens, amygdala, hippocampus, and thalamus volume. Also, the statistically significant difference in the volume between methamphetamine users and non-users was found in subcortical regions except putamen by age. Volumetric analysis of methamphetamine use in adolescents confirms a reduction in temporal lobes (methamphetamine users M±SD=3.43±0.18 non-users M±SD=3.48±0.22) and parietal lobes (methamphetamine users M±SD=2.23±0.24, non-users M±SD=2.37±0.33) in cortical regions in the brain as tissue volume. However, methamphetamine uses caused an increase in volume in the subcortical regions.

Conclusion: Methamphetamine use appears to show decreased volume in the brain regions with age, which has adverse effects on cognitive, emotional, memory, and social abilities.

Keywords:. Methamphetamine, brain volume, adolescent, cortical, subcortical regions

Öz

Amaç: Bu çalışma metamfetamin kullanan ve kullanmayan ergenlerin beyin kortikal ve subkortikal bölgeleri dahil olmak üzere beyin yapı hacimlerini karşılaştırmayı amaçlamıştır.

Gereç ve Yöntem: Kesitsel olarak tasarlanan bu çalışmaya on metamfetamin kullanan ve dokuz metamfetamin kullanmayan ergenler dahil edilmiştir. Katılımcıların beyin görüntüleri magnetik rezonans görüntüleme cihazı ile elde edilmiş ve görüntülerin analizi volBrain program aracılığıyla yapılmıştır.

Bulgular: Sonuçlar metamfetamin kullanıcılarının temporal, parietal, nükleus akkumbens, amigdala, hipokampüs ve talamus bölgelerinde hacimsel değişikler olduğunu göstermiştir. Ayrıca, metamfetamin kullanan ve kullanmayanların subkortikal bölgelerinde, putamen bölgesi dışında, hacimsel değişikliğin yaşa göre istatistiksel anlamlılık gösterdiği bulunmuştur. Ergenlerde metamfetamin kullanımına ilişkin hacimsel analiz sonucunda temporal lobda (metamfetamin kullananlar M±SD=3.43±0.18, kullanmayanlar M±SD=3.48±0.22) ve parietal lobda (metamfetamin kullananlar M±SD=2.23±0.24, kullanmayanlar M±SD=2.37±0.33) hacimsel azalma olduğunu tespit edilmiştir. Ancak metamfetamin kullanımı subkortikal bölgelerde hacim artışına neden olmuştur.

Sonuç: Metamfetamin kullanımın yaşa bağlı olarak beyin bölgelerinde hacimsel değişime neden olduğu, bununla beraber kullanıcıların bilişsel, duygusal, hafıza ve sosyal becerileri üzerinde olumsuz etkiler oluşturduğu söylenebilir.

Anahtar kelimeler: Metamfetamin, beyin hacmi, ergen, kortikal, subkortikal bölgeler

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INTRODUCTION

Substance use is a growing primary health concern affecting adolescents' brain structure negatively. The adolescence period is an essential cycle for individuals whose immature cognitive abilities make adolescents vulnerable to substance addiction. One of the common illicit drugs is methamphetamine (MA), a synthetic substance that has a stimulating effect on the brain structure, and it can be taken orally, snorted, and used intravenously because of its lipophilic character[1]. Adolescents did not frequently use MA historically, but the number of MA users has been increasing rapidly in recent years, and there are an estimated more than 35 million MA users worldwide[2]. MA use in Turkey is one of the most prevalent drug abuse among adolescents. Although the study's findings indicate that the amphetamine/methamphetamine group has been the most often used substance group over the last two years[3], the exact number of methamphetamine users in Turkey is unknown.

Numerous neuroimaging studies have been performed to highlight the functional and structural brain abnormalities in adolescents with illicit drug abuse[4,5]. Because the adolescent period is a critical developmental cycle for cortical functioning, such as attention, decision-making, working memory, language, and vision are still developing. Therefore, substance misuse and risky behavior escalation are more likely to occur in adolescence. Although volumetric studies are rapidly growing, to the best of our knowledge, there is still a gap about MA use's impact on adolescents' cortical thickness. Interestingly, this may be the first study to investigate the association between cortical thickness and MA use in adolescents.

The fMRI studies in MA dependence have reported decreased altered cortical activation and deficits in cognitive tasks in recently absent MA-dependent males[6,7]. Jernigan et al.[8] reported that higher parietal grey matter volume and parietal lobe (angular gyrus, precuneus, and superior parietal lobules) were associated with a higher level of neurocognitive impairments. Another study by Thompson et al.[9] noted that increased volume in the parietal lobes is associated with neurodegenerative changes in MA abusers. Another study found thinner bilateral insula, left middle frontal gyrus, and left superior frontal gyrus in MA users compared to healthy controls[10].

Even though there is less research on cortical thickness for MA users, some studies have been done about cortical thickness in online gaming addiction in adolescents[11], substance use disorders in female adolescents[12], synthetic cannabinoid users[13], and marijuana users in adolescents[14] strongly suggest that prefrontal cortex, temporal lobe, parietal lobe and some subregions of occipital lobe are involved different substance abuses. For example, Nakama et al.[15] examined the regional volume of grey matter in adult MA users compared to control subjects. They found smaller dorsolateral prefrontal cortex (DLPFC), orbitofrontal cortex (OFC), prefrontal cortex (PFC), limbic, and insular lobes in addition to frontal, temporal, and parietal lobes.

Earlier research has demonstrated that changes in brain morphology and cortical thickness throughout time are associated with aberrations in drug addiction to substances like alcohol[16],cannabis[17], and marijuana[18]. The impact of MA misuse on adolescent cortical and subcortical regions is not well-documented. This study assessed explicitly in MA dependents differences in cortical (parietal and temporal) and subcortical regions from non-users in the volume of the temporal, parietal lobes, nucleus accumbens, amygdala, hippocampus, putamen, and thalamus.

Although there have been many studies investigating illicit drugs and their effect on adolescents' brain structure, there is a gap in the literature to investigate the effects of MA using in cortical and subcortical regions in adolescents in Turkey. Therefore, the purpose of this study is to assess the effect of MA using in cortical (parietal and temporal) and subcortical regions from non-users in the volume of the temporal, parietal lobes, nucleus accumbens, amygdala, hippocampus, putamen, and thalamus.

MATERIALS AND METHODS

Sample

The study comprised nine non-user subjects—four male and five female—and ten patients who had used methamphetamine for at least a year. The subjects were all between the ages of 12 and 17. Participants were gathered through snowball sampling which is a non-probability sampling method where new units are recruited by other units to form part of the sample. All subjects had to be between the ages of 12 and 17. Users of MA included a self-report of MA consumption for at least more than a year, and the

control group's health was shown to be in good shape. Sample size calculations alpha error was taken as 5%, beta error as 20%, and power analysis as 80% in the sample size calculated for power analysis. Then, minimum sample size was determined as ten for the study.

The following were included as exclusion criteria for MA users: consumption of MA for less than a year, history of neurological disease, head injury, or neurosurgery, any recognized psychiatric disorder, current pregnancy, and MRI contraindications. Except for MA use, the non-users satisfied the same exclusion criteria. Before the MRI screening, all patients received a warning to remove any objects and had a clinical and diagnostic semi-structured interview with radiologists and doctors. Fifteen MA users were approached for the study but five of them did not complete the MRI processing due to fear of MRI and they were excluded from the study.

In addition, assessments of adolescents' resilience, satisfaction with life, psychological well-being, and quality of life were made. All participants in the research, including parents, provided signed informed consent. The Kapadokya University Ethics Committee approved the study (Protocol No: 29533901-050.99-21530 with the date of 08/29/2022).

Data collection

MRI image acquisition

A 3T MR system (Siemens, Medical Solutions, Erlangen, Germany) was outfitted with a standard quadrature head coil for MRI scanning. A T1-weighted magnetization-prepared rapid gradient echo image and volume were acquired during structural acquisitions. The following parameters were used: TR/TE/TI=1900/2.21/900 ms, voxel size=1 mm, slice thickness=1 mm, FoV=165250 mm, number of slices=126, flip angle=15°, and number of participants=20 (mean age 16.8 for MA and 14.8 for non-users). After all set up, cortical (parietal and temporal) and subcortical regions were imaged for MRI. The study was conducted at Erciyes University Research Hospital Radiology Department. MRI scans were conducted and supervised by the neuroradiologist from Radiology Department from the Erciyes University Research Hospital. MRI acquisition was done the date between December 2022-February 2023. Psychological scales were applied to participants during these dates before the MRI acquisition was done.

MR image processing

All MR scans were controlled and assessed virtually before processing in a web-based volume computation called VolBrain (https://volbrain.upv.es/), which aims to analyze brain imaging data automatically. As a black box solution, VolBrain acquires anonymized MRI brain volumes in NIFTI format and then generates a report in pdf format that includes the volumes of the primary intracranial tissues (ICC) (i.e., CSF, WM, and GM), as well as volume data of macroscopic areas such as the cerebellum, brain hemisphere, and brainstem. Additionally, segmentation of the subcortical structures is automatically accomplished, and the label maps and volumes are supplied. The average processing time is 15 minutes. However, the scan time may vary depending on how many jobs are waiting in line on the web server.

Measures

Adolescent Resilience Scale

The scale was developed by Bulut et al.[19]. The scale applied to adolescents aged 14-18 was prepared in a 4-point Likert type (1 not suitable for me at all - 4 very suitable for me). The scale consists of 6 sub-dimensions and 29 items: family support, peer support, school support, adaptation, determination to struggle and empathy. The scores that can be obtained from the scale vary between 29 and 116. On the contrary, items will be calculated by reverse scoring method, and high scores indicate high psychological resilience of the adolescent. While the option "Not at all suitable for me" will be given "1" point, the option "Very suitable for me" will be given "4" points. The scale Cronbach Alpha internal consistency coefficient values found .87 for the whole scale, .89 for the family support, .89 for the peer support, .81 for the school support, .70 for the adaptation, .67 for the determination to struggles, and .61 for the empathy sub-dimensions.

Satisfaction with Life Scale

The scale was first developed by Diener et al.[20] was developed by. Likert-type scale consisting of 5 items: strongly disagree (1), disagree (2), partially disagree (3), neither agree nor disagree (4), partially agree (5), agree (6) contains statements such as “I totally agree” (7). All of the expressions in the scale have positive

meanings, there is no reverse scored item, and the scale consists of one dimension. The minimum score that can be obtained from the Life Satisfaction Scale is 5, and the maximum is 35. A low score on the scale indicates a low level of life satisfaction, and a high score indicates a high level of life satisfaction. The Cronbach alpha value of the scale was found to be .87. Turkish adaptation of the scale was done by Yetim[21] and the Cronbach alpha value was found to be .86 and the test-retest reliability was found to be .73. The Cronbach Alpha coefficient of the scale calculated in this study is .79.

Five-Dimensional Well-Being Scale for Adolescents

The scale was first developed by Kern et al.[22] and was adapted into Turkish by Demirci and Ekşi[23]. The scale is prepared according to the 5-point Likert type and the answers are scored between 1 and 5. There are a total of 20 items and 5 subscales: "commitment", "determination", "relatedness", "optimism" and "happiness" exists. While the average of the scores from the subscales can be used to score the scale, inferences can also be made from the total well-being score. The internal consistency coefficient of the scale is .95, item-total score correlations range between 41. and .77. In this study, the Cronbach's alpha value of the scale was found to be .92.

Pediatric Quality of Life Questionniare (PedsQL)

The scale developed by Varni et al.[24] aims to measure the general quality of life in the 2-18 age group. The scale has four separate forms for the 2-4, 5-7, 8-12 and 13-18 age groups, arranged according to age group characteristics. 13-18 form age group was used in this study. The scale measures physical, emotional, social, and academic functioning. It consists of four subsections in which questions are questioned. There are eight items in the physical functionality section, five items in the emotional functionality section, five items in the social functionality section, three items in the 2-4 age group in the school-related problems section, and five items in other age groups. A Turkish validity and reliability study was conducted for the PedsOL for the 2-18 age group[25]. The internal consistency of the scale was found to be 0.82 for the adolescent form and 0.87 for the parent form for the 13-18 age group. When the correlations between adolescent and parent forms are evaluated. Statistically significant and directly proportional correlations were obtained. In this study, Cronbach's alpha value was found to be .80.

Statistical analysis

Demographic characteristics and psychological scales were performed in SPSS Statistics version 25 and VolBrain program version 1. For the comparison of brain volumes between methamphetamine users and non-users, mean, standard deviation, Kolmogorov-Smirnov normality test, student t-tests, Chi-square, Fisher's exact test, and analysis of covariance (ANCOVA) were used. ANCOVA was used to assess whether age affects temporal and parietal lobes and their subregions of the central brain regions. Age-related volume differences were also assessed in subcortical regions of the brain. The statistical significance set was $p<0.05$.

RESULTS

Demographic characteristics and data comparison are presented in Table 1. Ten methamphetamine users and nine non-users were included in the data analysis. Thirteen participants were male, and 6 of them were female among all participants. The mean age of MA users was 16.8 years (SD=1.27), and non-users was 14.8 years (SD=0.9), range 12-17 years. The two subject groups did not have statistical significance for age ($p=0.22$) and gender ($p=0.26$) (Table 1). Regarding the MA usage year, the time of usage of MA did not show statistical significance. Also, compared to non-users, MA users had fewer mean scores of Resilience, Satisfaction with Life, Psychological Well-Being, and Quality of Life.

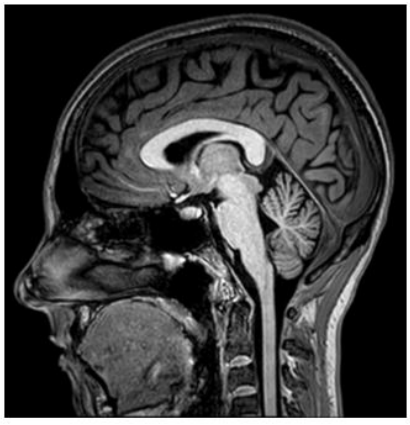

Figure 1. A mid-sagittal view of the 3D-T1W image obtained by MRI examination was shown.

Table 2 compares cortical and subcortical regions volume for MA users and non-users, as MA users showed slightly smaller cortical volumes than non-users. The smallest volume was measured in the postcentral gyrus in the parietal lobe of MA users and non-users (p=0.92). Only a significant region was reached in the angular gyrus in the parietal lobe (p=0.01). However, among the five subcortical regions, the nucleus accumbens, amygdala, hippocampus, and putamen showed slightly greater volume in MA users than non-users. Only the thalamus subregion in the subcortical cortex showed a smaller volume in MA users than in non-users. In addition, among five subcortical regions, significance was reached in the thalamus (p=0.04).

Table 1. Demographic information and characterization of participants

Group	MA user (N=10) M (SD)	Control (N=9) M (SD)	p-value
Age	16.8 (1.27)	14.8 (0.9)	t(8)=1.23,p=0.22
Gender (M/F)	9(90%)/1(10%)	4(45%)/5(55%)	X^2 (1,n=10)=1.14,p=0.26
Year of MA use	4.8 (0.61)	n.a.	n.a.
ARS Total	2.1 (0.52)	2.8 (0.89)	t(8)=_2.64,p=0.95
SLC Total	4.2 (1.2)	4.9 (1.8)	t(8)=3.174,p=0.60
EPOCH Total	2.8 (0.18)	3.24 (0.15)	t(8)=2.66,p=0.52
PedsOL Total	2.8 (0.74)	3.1 (0.86)	t(8)=1.93,p=0.34

ARS: Adolescents Resilience Scale, SLC: Satisfaction with Life Scale, EPOCH: Five-Dimensional Well-Being Scale for Adolescents, Pediatric Quality of Life Questionnaire (PedsQL)

Table 2. Cortical and subcortical volume comparison of Methamphetamine Users and Non-users

Brain region (mm)	MA users (n=10)	Control (n=9)	t-test p-value	ANCOVA (drug by age interaction) p-value
Temporal Lobe	3.43±0.18	3.48±0.22	t(8)=1.62,p=0.22	F(1,7)=0.89,p=0.02
Planum polare	2.25 ±0.32	2.29 ±0.37	t(8)=1.84,p=0.18	F(1,7)=0.93,p=0.770
Middle temporal gyrus	3.40±0.19	3.56±0.25	t(8)=0.32 p=0.78	F(1,7)=0.28,p=0.870
Sup. temporal gyrus	2.83±0.15	2.89±0.36	t(8)=1.42,p=0.11	F(1,7)=0.37,p=0.853
Transverse temporal gyrus	2.40±0.23	2.43±0.29	t(8)=0.32,p=0.66	F(1,7)=1.08,p=0.333
Temporal pole	3.96±0.26	3.99±0.30	t(8)=1.03,p=0.30	F(1,7)=0.070,p=0.90
Parietal lobe	2.23±0.24	2.37±0.33	t(8)=0.92,p=0.88	F(1,7)=0.398,p=0.01
Angular gyrus	2.67 ±0.27	2.89 ±0.41	t(8)=2.02,p=0.01	F(1,7)=1.44,p=0.268
Postcentral gyrus	1.50±0.27	1.57 ±0.26	t(8)=1.28,p=0.92	F(1,7)=0.626,p=0.455
Precuneus	2.92±0.25	3.05±0.25	t(8)=1.18,p=0.72	F(1,7)=0.10,p=0.01
Sup. parietal lobule	1.64±0.29	1.86±0.32	t(8)=1.94,p=0.38	F(1,7)=0.915,p=0.116
Supramarginal gyrus	2.55±0.31	2.65±0.39	t(8)=1.51,p=0.44	F(1,7)=0.960,p=0.121
Subcortical regions (cm^3)				
Nucleus accumbens	0.78±0.86	0.74±0.08	t(8)=0.85,p=0.41	F(1,7)=0.09,p=0.01
Amygdala	2.19±0.29	2.06±0.18	t(8)=0.97,p=0.82	F(1,7)=0.183,p=0.02
Hippocampus	8.56±0.85	8.28±0.62	t(8)=0.27,p=0.34	F(1,7)=0.21,p=0.000
Putamen	9.84±0.70	9.77±0.81	t(8)=1.85,p=0.07	F(1,7)=0.531,p=0.094
Thalamus	13.3±1.10	13.48±1.12	t(8)=2.12,p=0.04	F(1,7)=0.387,p=0.04

MA: Methamphetamine users, Data are presented as mean ± standard deviation.Significant p-value p<.05.

The effect of age on cortical and subcortical brain volumes was computed between the two groups, and the results were markedly different. Among the main brain lobes, ANCOVA interaction results showed that the MA users show greater than normal-aged related cortical volume loss compared to non-users in temporal (p=0.02) and parietal (p=0.01) lobes. In addition, statistical significance was reached in precuneus in the parietal lobe (p=0.01), while no significant drug status by age interaction was

observed in subregions of the temporal and parietal lobes. When the ANCOVA test was performed in subcortical regions, significance was reached in the nucleus accumbens (p=0.01), amygdala (p=0.02), hippocampus (p=0.00), and thalamus (p=0.04). Statistical significance was not only seen in the putamen in subcortical regions (p=0.094). It is also seen that the main lobes and their subregions are larger than the sum of the subcortical regions.

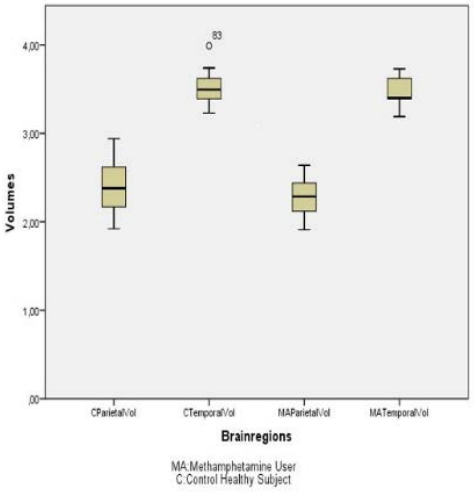

Figure 2. The box plot diagram shows volume differences (shown in cm3 on the y-axis for brain regions of temporal and parietal lobes)

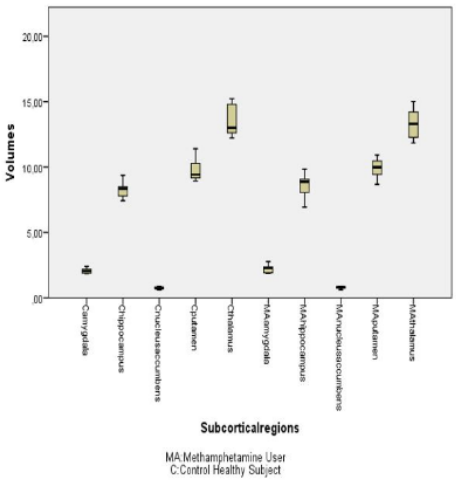

Figure 3. The box plot diagram shows volume differences (shown in mm on the y-axis for subcortical regions for nucleus accumbens, amygdala, hippocampus, putamen, and thalamus) in methamphetamine users and non-users.

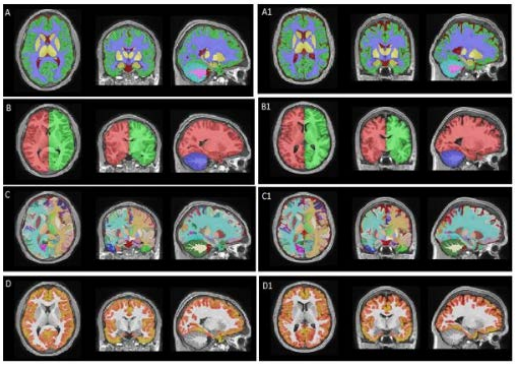

Figure 4. Structural Boundaries for Volume of Cerebral Cortex and Subcortical Structures for Methamphetamine Users: A-D: Tissue segmentation, Macrostructure, Structure segmentation, and Cortical thickness for methamphetamine users, A1-D1: Tissue segmentation, Macrostructure, Structure segmentation, and Cortical thickness for non-users.

DISCUSSION

The current study evaluated brain structure volume in methamphetamine users versus non-users in adolescents. When compared to the non-users, MA users have volume reduction primarily in the parietal lobe, superior parietal lobule, precuneus, middle parietal lobule, middle temporal gyrus, superior temporal gyrus, transverse temporal gyrus, temporal pole, and angular gyrus. MA users also have more volume in subcortical areas such as the putamen, amygdala, nucleus accumbens, and hippocampus. The findings indicated that, as compared to the non-users, MA users exhibit volume loss mainly in the temporal and parietal lobes and their subregions and volume increase in all subcortical brain regions other than the thalamus.

Previous MRI studies mainly measured total brain volumes, white matter (WM), and grey matter (GM) between MA users and control groups[7-26]. However, it is unfortunate that structural MRI has only occasionally been performed on MA users. To the best of my knowledge, this is one of the first studies

to evaluate the volume of brain macro and microstructures, mainly in Turkish adolescents' temporal, parietal lobes, and subcortical regions. The study by Nakama et al.[15] reported that MA users have reduced grey matter in frontal, temporal, occipital, and insular lobes, making MA users vulnerable to cognitive tasks and abilities. These results are partly in line with Thompson et al.[9], which found a reduction in the grey matter of the cingulate and other subcortical regions in the right hemisphere.

A study by Grant et al.[27] found that reduction volume in the temporal lobe is marked in MA users with severe psychosis, and continuous volume reduction in the superior temporal gyrus is associated with florid psychosis[28]. The present study found reduced volume in the superior temporal gyrus in the MA users compared to non-users. Thus, it can be said that MA users may experience most often reported psychiatric symptoms, including hallucinations and psychosis, because of volume reduction in temporal lobes. Another relevant study[29] reported decreased volume in striatal and parietal lobe structures in MA dependent, associated with developmental and antisocial personality disorders.

The studies in MA users have found different results in the brain's cortical and subcortical regions. For example, the study by Volkow et al.[30] reported that MA use tends to increase brain glucose levels in all brain cortices as glucose metabolism was found higher in the parietal cortex but lower in the thalamus, putamen, caudate, and the striatum. Wang et al.[31] revealed that the thalamus regional metabolism activity increased when MA was exposed to abstinence for months. The studies reported that MA uses and abstinence may lead to motor, verbal memory tasks, neurological, and psychological impairments. The morphometric studies in MA users also reported altered brain cortical and subcortical regions linked to acute complications, long-term neurotoxicity, and neuropsychological effects of drug dependency[32]. The study by Friedman et al.[33] has found larger grey matter volume in the striatum and bilateral parietal cortex, while Rothman et al.[34] have found less grey matter volume in the mid-frontal, cingulate, limbic, and temporal cortices of MA users. The present study results align with the findings, which found decreased volumes in temporal lobes, planum polare, mid-temporal gyrus, sup-temporal gyrus, transverse temporal gyrus, and temporal pole. The results are inconsistent with the findings of Schwartz et al.[10].

However, the present study results contradict a previous study of average age-related cortical grey matter loss, which identified decreased cortical thickness in 17 sub-regions[15]. Wrase et al.[35] reported decreased volume in the amygdala, which could result in increased craving and predictive relapse. The present study results align with another previous study, which found increased volume in the nucleus accumbens, putamen, caudate, and globus[9]. Although there is limited information regarding volume alteration in the subcortical volumes in MA users, the present study findings reported increased volume in the nucleus accumbens, amygdala, hippocampus, and putamen, but only decreased volume was observed in the thalamus. Furthermore, including the present study results, previous studies in MA users found decreased cortical thickness in the temporal and parietal lobes. The results also found a thinner thalamic region in the MA users, part of the limbic cortex. The reduced cortical thickness in the thalamus has been implicated in impairments in the body's senses, including motor movement, sensory information, processing, and interpretation of the cerebral cortex.

Little evidence in the literature supports increased volume in subcortical regions among MA users, despite studies consistently focusing on changes in grey and white matter volume in the central brain lobes. Therefore, the current study's findings are invaluable, especially in subcortical regions. Furthermore, the current study showed no significant difference between MA users and non-users in the putamen for volume. However, there were significant variations between the two groups in the nucleus accumbens, amygdala, hippocampus, and thalamus for volume. The results of the current study are consistent with those of prior investigations into substance abuse, including one by Olak et al.[13], who discovered that users of synthetic cannabinoids have a larger nucleus accumbens. However, Durazzo et al.[36] discovered decreased volume in the insula, amygdala, hippocampus, and superior frontal gyrus of alcohol addicts. Additionally, among users of alcohol, cocaine, and cannabis, the length of abstinence was positively correlated with nucleus accumbens, putamen, and amygdala volume[37]. The subcortical regions of the brain appear to be affected by various substance usage, and the present study may emphasize changes in the nucleus accumbens and amygdala volume.

Although there are some limitations to the study, this may be one of the first studies to compare volumes for brain structures in a sample of Turkish adolescents who use MA and non-users, despite the study's limitations. According to the current study, adolescent MA users showed increased volume in subcortical regions for the first time as the volume in the temporal and parietal lobes was reduced in MA users. These findings imply that MA use impairs social, emotional, cognitive, and memory functions.

The study presented findings that suggest methamphetamine users experience changes in brain structures, specifically the temporal lobes, parietal lobes, nucleus accumbens, amygdala, hippocampus, and thalamus volume. However, the limited number of participants and potential confounding factors may raise concerns about the reliability of the results. The future studies may consider the large sample size and consider of whole brain volume, white matter and grey matter between methamphetamine users and control group and compare those with the previous studies. Lastly, the study suggests that methamphetamine use leads to decreased brain volume in certain regions, which can negatively impact cognitive, emotional, memory, and social abilities. To avoid of subjective conclusion, the future studies may consider corresponding behavioral support.

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Peer-review: Externally peer-reviewed.
Conflict of Interest: Authors declared no conflict of interest.
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