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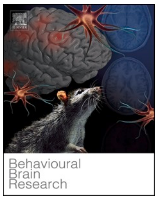

Research report

Brain changes following mindfulness: Reduced caudate volume is associated with decreased positive urgency

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ABSTRACT

Mindfulness training has been shown to improve psychological health and general well-being. However, it is unclear which brain and personality systems may be affected by this practice for improving adaptive behavior and quality of life. The present study explores the effects of a 5-week mindfulness-based intervention (MBI) at the neuroanatomical level and its relationship with dispositional mindfulness and impulsivity. Sixty-six risky drivers were quasi-randomly assigned to a mindfulness training group (MT) or a control group (N). Participants underwent magnetic resonance imaging and completed the Five Facet Mindfulness Questionnaire (FFMQ) and the UPPS-P impulsivity scale twice, at baseline and after receiving the MBI. We observed that MBI changes dispositional mindfulness in the non-reactivity and observing facets. Further, we observed that the magnitude of change in impulsivity was associated with the change in dispositional mindfulness. Whole-brain voxel-wise analysis revealed that the volume of the right caudate nucleus of the MT group ($n = 27$) showed a reduction compared to that of the control group ($n = 33$), which increased in terms of the pre-post measurement ($MT = -1.76\ mm^3$; $N = 6.31\ mm^3$). We also observed that reduced caudate nucleus volume correlated with decreased positive urgency in the MT group. Taken together, our results show that MBI improves the skills of observing and non-reactivity to inner experience, while producing changes in the structure of the caudate nucleus. These structural changes are associated with a reduction in impulsivity levels, decreasing the tendency to act rashly in situations that generate positive emotions and thus facilitating more adaptive behavior.

1. Introduction

Mindfulness is the act of intentionally paying attention to the present moment with acceptance, openness, and non-judgment [1]. This ability is conceptualized as a momentary condition and a stable characteristic or natural tendency of each individual [2]. Dispositional mindfulness has been related to various cognitive and personality factors involved in mental health, such as neuroticism, coping strategies, rumination, executive functions, and impulsivity [3]. Although dispositional mindfulness is independent of mindfulness practice [4], it has been found that mindfulness skills training can produce more than short-term state changes, leading to an increase in trait characteristics [5] and modifications in brain anatomy [6–8]. In addition, mindfulness practice has been shown to produce improvements in psychological health and general well-being [9,10]. Although the beneficial effects of mindfulness have been widely studied, there is debate regarding which brain and personality systems may be affected by this practice to improve adaptive behavior and quality of life [11]. We aim to address this gap by further studying the effects of mindfulness training at the neuroanatomical level while exploring its relationship with certain personality traits, such as dispositional mindfulness and impulsivity.

As a personality trait, the UPPS model [12] proposes that impulsivity is a multidimensional construct characterized by the lack of premeditation and/or perseverance when acting, risk-taking or sensation-seeking behaviors, and the tendency to act rashly in highly emotional situations. At the brain level, the different dimensions of impulsivity have been related, both in a general and clinical population, to the brain networks responsible for response inhibition, reward

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valuation, and emotional regulation [13,14]. Nevertheless, previous studies on the association between gray matter volume (GMV) and impulsivity have yielded mixed results. For example, lack of perseverance and sensation seeking have been negatively related to the anterior cingulate cortex (ACC) and amygdala, respectively [15]. However, both positive and negative associations between negative urgency, positive urgency and lack of premeditation with the frontal pole and striatum have been found [16–21]. So more research is still needed to clarify the neuroanatomical basis of impulsivity.

As a construct of considerable relevance for mental health, various impulsivity factors have been related to mindfulness and its facets. However, the results on the magnitude and direction of the associations vary across studies. It is generally observed that many of the dimensions of impulsivity are negatively associated with the different facets of mindfulness (e.g., negative urgency with non-reactivity or awareness with lack of perseverance), whereas others show no significant relationships (e.g., sensation seeking with non-reactivity) [22–25]. In addition, positive relationships have also been found between the different factors of both variables (e.g., observing with positive urgency and sensation seeking [24,25]. Despite the evidence concerning the association between mindfulness and impulsivity, studies that have investigated the effects of mindfulness-based interventions (MBI) on impulsivity are scarce and were designed to address very specific mental disorders, such as ADHD and addictive disorders [26,27]. For example, Davis et al. [28] found that young adults who received a Mindfulness-Based Relapse Prevention (MBRP) treatment showed significant reductions in all facets of impulsivity, except sensation seeking. However, Maddox [29] found that MBRP did not improve any of the dimensions of impulsivity. Therefore, further research is needed to determine how mindfulness training influences impulsivity.

Aside from modifying various cognitive and personality processes, MBIs can affect brain anatomy. Both increases and decreases in GMV have been observed in cortical (e.g. prefrontal, somatosensory, parietal and cingulate cortices) and subcortical (e.g. amygdala, insula, caudate, thalamus, precuneus, hippocampus) structures after MBIs [30–36]. However, changes in the anatomical brain configuration after mindfulness training have been related to a lesser extent to the cognitive, emotional, or personality processes thought to underpin mindfulness skills. For example, Hölzel et al. [37] found that a reduction in perceived stress after an 8-week Mindfulness-Based Stress Reduction (MBSR) intervention correlated with a reduction in gray matter density in the amygdala. Fahmy et al. [30] found that increased prefrontal/ACC network volume after MBSR was associated with reduced negative urgency. In contrast, Yu et al. [35] found that brain structure changes after mindfulness training did not correlate with changes in different cognitive domains, such as attention or working memory.

Despite the evidence regarding the association between mindfulness and impulsivity and the changes of mindfulness practice on brain structure, there is a clear need to study further how these changes relate to cognitive or personality processes that influence mental health and general well-being. This study aimed to explore the effects of a mindfulness-based intervention on brain structure and determine how these effects relate to changes in impulsivity and trait mindfulness. We hypothesized that mindfulness training might reduce impulsivity levels, increase dispositional mindfulness and affect structures related to self-regulation and impulsivity Tang et al. [8].

2. Material and methods

2.1. Participants

Participants in this study were part of a larger study (ERPAT) to determine the brain basis of risk behavior in risky traffic scenarios. We used structural MRI from 66 participants (19 women, 34.2 years old, age range= [19,63]). Six participants were discarded due to bad quality MRI images and missing data in questionnaires. None of the participants reported a history of head injury nor a history of neurological disorders. All participants were scanned twice — at baseline and after receiving a mindfulness intervention devoted to correcting their risky behavior. All participants signed an informed consent form, were informed of their rights, and were treated according to the Helsinki Declaration [38]. All participants were paid for their participation in the study. The Ethics Committee of Human Research of the University of Granada approved this research (204/CEIH/2016). To have a power of 0.80, the sample size was calculated as 60 participants with G-power, with a partial R-square of 0.028 and 0.8 correlation between the repeated measures.

2.2. Procedure

Participants were risky individuals recruited from the traffic driving school of Granada where they were recovering points on their driver license (n = 20) or from internet advertising (n = 46). All of them were asked to complete a questionnaire on traffic violations. To establish whether a participant was risky we used the following self-reported inclusion criteria: attendance of a rehabilitation course for drivers at least once, a loss of points according to the Spanish penalty system for traffic rule violations, being fined at least twice for risky driving behavior (alcohol or drug use, not using a seat belt, or exceeding speed limits), or reporting as having usually exceeded speed limits by more than 20% of the permitted speed. Participants were assigned to two groups dependent on their weekly availability. The first was a control group (N, n = 33, 33.3% females) that did not receive an intervention, while the second group received training in mindfulness meditation (MT, n = 27, 33.3% females). To gather the largest number of participants for the training group, the availability of the participants was established prior to testing. At four different times over the 2-year period of data collection, we grouped the participants with the same availability, resulting in a quasi-randomized controlled trial.

The mindfulness meditation intervention was aimed at improving risky driving (see Baltruschat et al. [39], for more details) and was based on the Mindfulness-Based Stress Reduction program (MBSR; [40]) but adapted to a five weeks duration (3 h sessions) due to the reduced availability of the participants. Sessions were prepared by a clinical psychologist (CVL) and were delivered by the clinical herself and another sanitary psychologist (ECV). Both were professionally accredited to deliver the MBSR program. However, neither of them was involved in the evaluation of data collection beyond the mindfulness programs. The sessions were designed to enhance situation awareness and included meditation (attention to breathing, body scanning, guided meditation) and yoga practice, groups discussion, as well as training in emotion regulation and the importance of focusing on what happens in the present moment, pausing to take a breath, observing both inside and outside and finally selecting the appropriate response. To ensure adherence to the intervention, participants were required to sign an attendance sheet and home practices were assigned after each session. The intervention was done immediately after the pre-test. The time elapsed between the pre and the post evaluations was around four months (mean = 143.07 days, SD = 69.68). There is no specific time interval after which the effects of mindfulness are evident [7], although previous studies have shown that mindfulness interventions (and others) have delayed effects on brain structure change [41–43].

2.3. Measures

The Spanish version of the Five Facet Mindfulness Questionnaire (FFMQ; [44,45]) measured dispositional mindfulness pre and post-intervention. This 39-item questionnaire has five scales and is rated on a 5-point Likert-type scale from 1 (never or very rarely true) to 5 (very often or always true). The questionnaire has good psychometric properties (Cronbach's: α = 0.88 for the whole scale, minimum Cronbach's α for the subscales = 0.80), and measures five facets of mindfulness: Observing (the attention paid to sensations and perceptions of inner and external stimuli); Describing (labeling experience and perceptions with words); Acting with awareness (the attention paid to one’s activities); Non-judging of inner experience (evaluation of one’s thoughts and feelings); and Non-reactivity to inner experiences (the ability to let thoughts and feelings come and go without getting caught up in them).

The Spanish version of the UPPS-P [12,46] was used to measure impulsivity at pre and post-intervention. This scale assesses impulsivity across five facets: (lack of) premeditation, (lack of) perseverance, sensation seeking, and negative and positive urgency. In addition, the scale has good psychometric properties (min Cronbach’s $\alpha = 0.61$).

MRI scanning was conducted with a Siemens 3T Trio system equipped with a 32-channel head coil at the Mind, Brain, and Behavior Research Center (University of Granada). Participants were instructed not to move during the scan. In addition, head restraint and foam padding around the head were used to limit head motion. A T1-weighted MPRAGE scan was obtained with a TR (repetition time) of 1900 ms, TE (echo time) of 2.52 ms, and a flip angle of 9°. For each volume, 176 slices of 1 mm thickness were obtained, which provide whole-brain coverage (voxel size = 1 ×1 ×1 mm; FOV = 256 mm; 256 ×256 data acquisition matrix).

The MRI scans were submitted to the CAT12 toolbox (http://www.neuro.uni-jena.de/cat/) to obtain brain volumes, running under the umbrella of SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/), using default parameters. In essence, CAT12 corrects for bias inhomogeneity, segmented into gray matter, white matter, and cerebrospinal fluid using the AMAP approach. The images were spatially normalized using the Diffeomorphic Anatomical Registration through Exponentiated Lie algebra (DARTEL) algorithm. Volumes were then normalized to the MNI neurological space and multiplied by the Jacobian determinant to preserve volume. Gray matter volumes were then smoothed using an 8 mm FWHM Gaussian kernel.

2.4. Data analyses

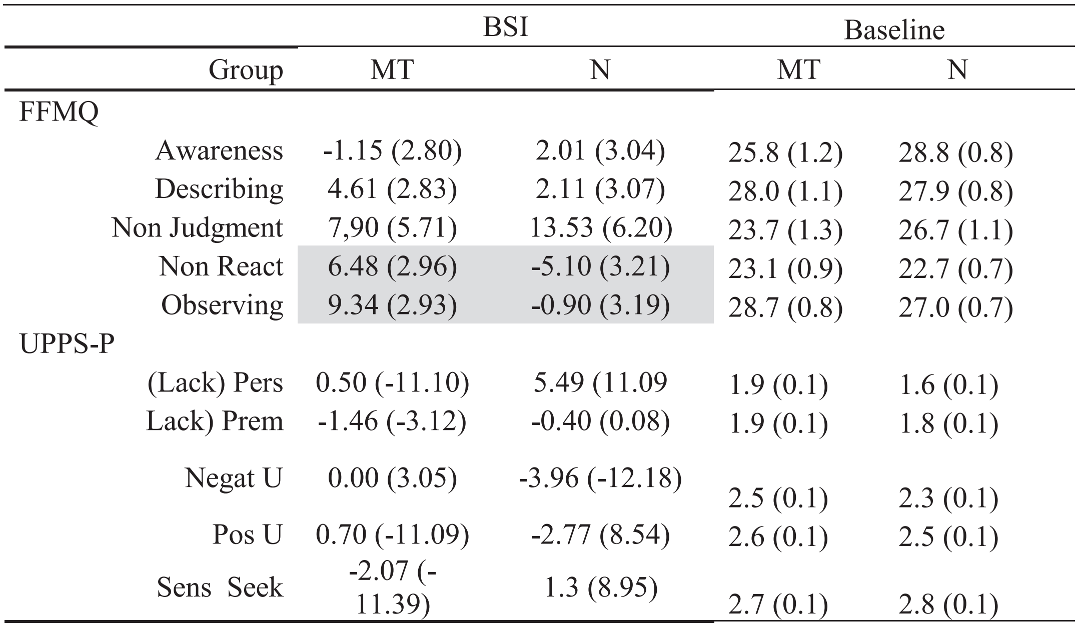
SPM 12 was used to conduct the whole-brain voxel-wise statistical analyses. Repeated measures factorial statistical analysis was used, in which comparisons between the two groups in the pre and post-intervention were made while controlling for age, gender, education level, and total gray matter volume. The significance threshold was cluster-wise corrected to $pFWE < 0.05$ with a minimum cluster size of $k = 200$ to handle the multiple comparison problem. FFMQ and UPPS-P scores were transformed to the behavior shift index (BSI;[47]), defined as the magnitude of change between baseline and post-intervention evaluation, using the formula (Post-Pre)/Pre* 100. Previous studies have used the BSI to examine the effects of mindfulness in different domains [39,48]. The Pearson correlation coefficient was used to evaluate the associations between the FFMQ and the UPPS-P scores. SPSS v 24 (IBM SPSS Statistics for Windows, Version 24.0, Armonk, NY: IBM Corp.) was used to analyze the effects of the intervention on the FFMQ dimensions and UPPS-P scores, using an analysis of covariance approach in which we controlled for the effects of age, gender, and education level.

3. Results

Table 1 displays the means (standard errors) for the BSI and baseline scores for the FFMQ and the UPPS-P scales. At the baseline, no significant differences were found between the MT and N groups in either the FFMQ or the UPPS, when the multiple comparisons problem was taken into account. Regarding the BSI, for the FFMQ dimensions, only the non-reactivity to inner experience, $F(1,56)= 7.65$, $p < 0.01$, which was greater for the MT (BSI=6.5) than for the N (BSI=−5.1) group, and the observing dimension, $F(1,56)= 5.24$, $p < 0.026$, which was also greater for the MT (BSI=9.3) than for the N (BSI=−.9) group, were significant. There were gender differences in the awareness dimension, $F(1,56)= 5.27$, $p < 0.01$, this score being higher for women (BSI= 7.9) than men (BSI=−3.2). There were neither main nor interaction effects on impulsivity scores ($p > 0.10$). However, there was an effect of education level on (lack of) perseverance, $F(1,56)= 9.38$, $p < 0.01$, and (lack of) premeditation, $F(1,56)= 6.30$, $p < 0.01$. In both cases, the higher the education level, the lower the impulsivity score.

Table 2 summarizes the results obtained at the brain structural level (Changes in GMV) in this study. We observed main effects of the intervention group in three clusters, one located in the left precuneus and the others located in the left temporal inferior and right fusiform, with GMV being larger for the MT group than for the N one group. We also observed an effect of the pre>post contrast in clusters located in the

Table 1
Behavioral Change ((post-pre)/pre* 100) and baseline scores as a function of group and dimensions of the FFMQ and UPPS-P.



	BSI		Baseline	
Group	MT	N	MT	N
FFMQ				
Awareness	-1.15 (2.80)	2.01 (3.04)	25.8 (1.2)	28.8 (0.8)
Describing	4.61 (2.83)	2.11 (3.07)	28.0 (1.1)	27.9 (0.8)
Non Judgment	7,90 (5.71)	13.53 (6.20)	23.7 (1.3)	26.7 (1.1)
Non React	6.48 (2.96)	-5.10 (3.21)	23.1 (0.9)	22.7 (0.7)
Observing	9.34 (2.93)	-0.90 (3.19)	28.7 (0.8)	27.0 (0.7)
UPPS-P				
(Lack) Pers	0.50 (-11.10)	5.49 (11.09	1.9 (0.1)	1.6 (0.1)
Lack) Prem	-1.46 (-3.12)	-0.40 (0.08)	1.9 (0.1)	1.8 (0.1)
Negat U	0.00 (3.05)	-3.96 (-12.18)	2.5 (0.1)	2.3 (0.1)
Pos U	0.70 (-11.09)	-2.77 (8.54)	2.6 (0.1)	2.5 (0.1)
Sens Seek	-2.07 (-11.39)	1.3 (8.95)	2.7 (0.1)	2.8 (0.1)

Note. MT: mindfulness training, N: control. Standard errors are between parentheses. Shaded cells indicate significant differences.

Table 2
Significant effects of the repeated measures factorial on brain structure.

Label	k	Peak T	X	Y	Z	pFWE
MT > N						
L Precuneus	325	4.73	-18	-51	65	0.001
L Temporal Inf	309	4.65	-32	-30	-20	0.001
R Fusiform	290	4.16	-47	-35	-21	0.001
Pre > Post						
R Temporal Pole Sup	301	3.77	-21	8	-32	0.001
R Frontal Sup	232	3.85	36	63	-9	0.005
Post > Pre						
R Hippocampus	405	4.60	21	-30	9	0.048
Group by Pre-Post						
R Caudate	417	5.03	15	-15	18	0.001

Note. K is the size of the cluster in voxels. X, Y, and Z: coordinates in MNI space. MT: mindfulness training, N: control. pFWE= cluster-wise corrected p-values.

right superior temporal pole, and the right superior frontal, with GMV being greater in the pre than post-measurement. There was also a significantly greater post-pre difference in volume in the cluster in the right hippocampus. The group by pre-post interaction was significant at a cluster in the right caudate (Figs. 1 and 2), embracing parts of the right thalamus, with the post-pre difference being greater in the N (6.31 mm^3) than in the MT (−1.76 mm^3) group. Therefore, the right caudate appears to show a reduction in volume (compared with the control group) after the mindfulness intervention.

The post-pre change in the volume of the caudate cluster correlated negatively with the behavior shift index of impulsivity in the dimension of positive urgency in the MT group ($r = -0.46$, $z = -2.43$, $p = 0.05$), with a marginal and positive correlation in the N group ($r = 0.35$, $z = 1.79$, $p = 0.08$). The difference between these two correlations was also significant, using the Fisher Z score ($z = 3.15$, $p = 0.001$). The change in caudate volume in the MT group implies that a lower caudate volume is associated with lower impulsivity in the post than in the pre-assessment. No correlations were significant for this brain cluster and BSI indices in the FFMQ (all $p > 0.10$).

The partial correlations, controlling for age, gender, and education level, between the BSI indices of the FMMQ and those of the UPPS-P, are displayed in Table 3, which shows that the BSI indices of positive urgency are positively associated with that of awareness and that sensation seeking is positively correlated with awareness and describing.

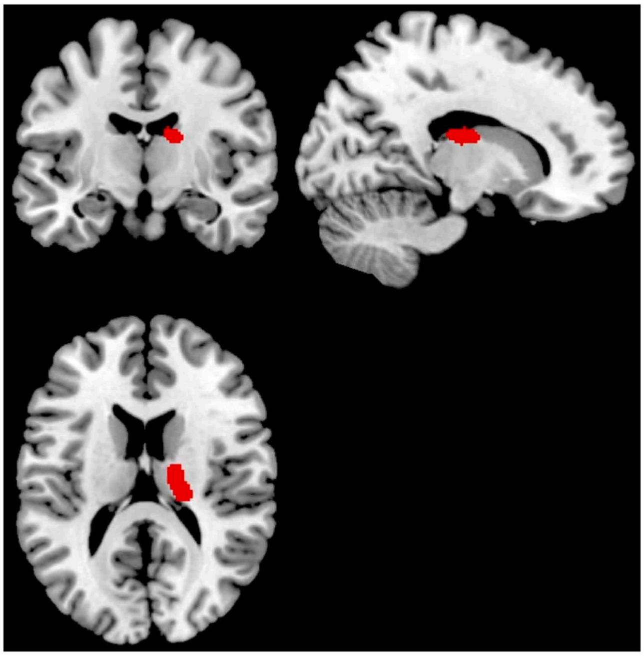


Fig. 1. Post-pre comparison of the caudate cluster, showing reduced volume in the MT than the N group.

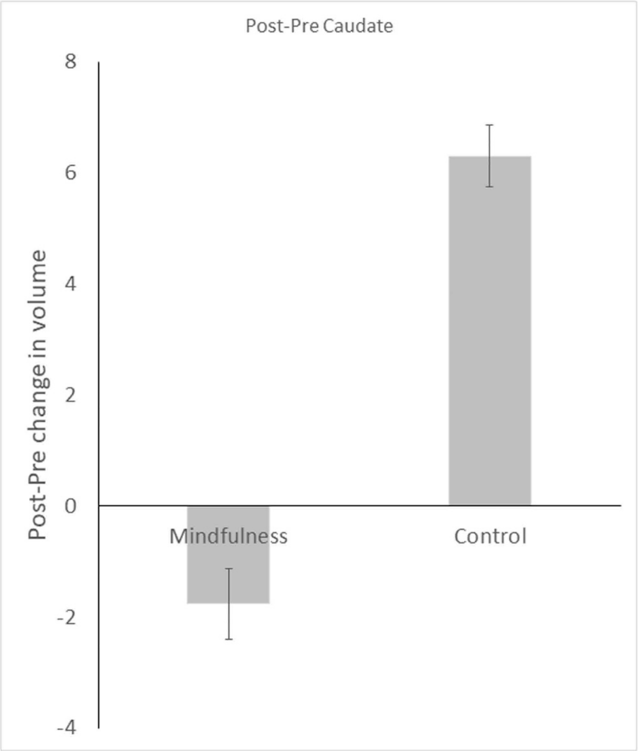


Fig. 2. Post-Pre differences in volume (mm^3) for MT and N group.

4. Discussion

This study aimed to reveal the effects of mindfulness training in structural gray matter volumes and how these effects are related to impulsivity and dispositional mindfulness using a quasi-randomized pre-post mindfulness intervention design. We have observed that mindfulness training changes dispositional mindfulness as measured by the FFMQ questionnaire in the non-reactivity and observing facets. In both facets, the MT group scored higher in the post than in the pre-test compared with the control group. Further, we have observed that positive urgency was positively associated with change in awareness; the greater the change in positive urgency, the greater the change in awareness. Sensation seeking was also positively associated with awareness and describing. At the brain level, we found that the volume of the right caudate nucleus of the mindfulness training group was smaller than that of the control group in the post-measurement. We also observed that the change in caudate nucleus volume correlated with decreased positive urgency in the MT group.

After mindfulness training, we found an increase in observing and non-reactivity scores in the MT group. This implies that certain facets of dispositional mindfulness could be susceptible to change due to mindfulness training. Numerous studies have investigated the effect of mindfulness-based interventions on enhancing mindfulness skills, understood as personality traits. Although some studies have found that mindfulness-based interventions have no specific effects on dispositional mindfulness [49–52], an increase in trait mindfulness is generally observed following such interventions [5,22,53–55]. This enhancement in dispositional mindfulness has been differentially attributed to one or more of the dimensions studied, depending on the characteristics of the intervention, the degree of control, and the population under study [5].

On the other hand, several investigations also conclude that the

Table 3
Partial correlations between BSI indices for UPPS-P and FFMQ. Shaded cells indicate significant association.

	Awareness	Describe	Non-Judge	Non-React	Observing
(lack of) Perseverance	-0.11	-0.04	-0.23	-0.04	-0.20
(lack of) Premeditation	-0.01	-0.19	-0.19	-0.09	0.18
Negative Urgency	0.06	-0.26	0.01	-0.01	-0.15
Positive Urgency	0.31	-0.14	-0.17	0.08	-0.05
Sensation Seeking	0.36	0.39	0.13	0.17	0.03

increase in the mindfulness trait is explained by an improvement in the abilities to observe or pay attention to one's perceptions and sensations and to let thoughts and emotions pass without clinging or reacting to them, observing an increase in the scores of these facets after various mindfulness-based interventions [34,56–58]. In addition, non-reactivity is the most significant contributor to overall well-being [59]. Therefore, our results are consistent with previous studies showing that mindfulness training improves dispositional mindfulness by increasing observing and non-reactivity abilities.

The dispositional mindfulness facets that improve after mindfulness training are those that show no significant relationships with the magnitude of change in the various dimensions of impulsivity. Previous research has also found inconsistent associations between the observing and non-reactivity facets with impulsivity [25,60–62]. Looking at the facets of mindfulness related to changes in impulsivity, we observed positive correlations between the BSI of awareness with positive urgency and sensation seeking and between the BSI of describing with sensation seeking. These results contrast with those obtained in previous studies, which found negative associations or no correlation between these variables [23–25,61], and indicate that people who tend to be aware of their current activities also tend to act rashly in the presence of positive emotions and seek out exciting activities. Impulsivity is a heterogeneous construct in which not all its factors are related, per se, to problematic behaviors [46]. In fact, and similar to our results, Vinci et al. [61] observed that sensation seeking and positive urgency were positively related to the state of mindfulness. Our results also support the notion [24] that mindfulness and impulsivity are related constructs with varying associations between the different factors that make up the two traits.

In addition to improving dispositional mindfulness, mindfulness training produces changes at the brain structural level. Our results showed a GMV reduction of the caudate nucleus in the MT group compared to the control group. The caudate nucleus has previously been implicated in mindfulness meditation and dispositional mindfulness. In dispositional mindfulness, the right amygdala and the caudate volume correlated negatively with the MAAS score [63]. In stark contrast, other authors [64] observed, in a cross-sectional study, a greater volume in the left caudate nucleus in an intervention group that received an MBSR course compared with an untreated group. In the same vein, Fahmy et al. [30] have observed increased volumes of the left caudate in a group of opiate-dependent patients receiving a MBI compared with a treatment as usual group.

Further, a MBI in patients with Parkinson's disease demonstrated that an eight-week program increased the density of the caudate compared with usual treatment [32]. Our data agree with those of Taren et al. [63] but disagree with the rest of the research. One possible explanation for these discrepancies could lie in the fact that in two of these studies [30,32], participants were from special populations (opioid-dependent and people with Parkinson's disease), which could suggest that the structure was already damaged at baseline but still recovers to a more normal volume due to the mindfulness intervention. Another possibility concerns the sample size and the reliability of the results [65], which is very high in the Taren et al. [63] study but low in the remaining studies. Furthermore, in line with our results, other research has found that expert meditators, compared to groups with no meditation experience, had lower GMV in several cortical and subcortical regions [66,67], including the caudate [67], although in the Korponay et al. [67] study these differences were not related to the total number of hours of practice.

The caudate has also been implicated in studies aimed at uncovering the brain's functionality and its association with mindfulness. Stillman et al. [68] found that the connectivity of the caudate with the medial temporal lobe (MTL) was negatively correlated with dispositional mindfulness during an implicit learning task. Given that the caudate-MTL connection is related to performance in implicit learning, this result suggests that greater dispositional mindfulness can hinder the acquisition of this type of learning and promote a more explicit learning mechanism. In this vein, an asymmetry has been found between the left and right caudate, in the sense that the left caudate is involved in the acquisition of habitual actions (mechanistic stimulus-response association) whereas the right caudate is involved in the acquisition of goal-directed actions [69–71]. Further, the caudate nucleus has shown to be a fundamental structure in acquiring stimulus-control associations, in which stimuli are associated with control states, such as heightened attentional selectivity [72]. In addition, Brefczynski-Lewis et al. [73] found that expert meditators had lower activation in the caudate, dorsolateral prefrontal cortex, and pulvinar when performing a task with distracting stimuli. In this vein, the right caudate might operate as a bottom-up controller [74], which is a more efficient behavioral control mechanism than the top-down processing initiated in the dorsolateral prefrontal or anterior cingulated cortex [75].

On the other hand, meditators have shown reduced activation of the caudate in anticipation of monetary rewards [76] and during positive emotional processing [77]. Moreover, the connectivity of this area with the posterior insula showed a negative association with dispositional mindfulness, [76]. As part of the reward processing network, it appears that the caudate — together with the amygdala — forms a microcircuit in which the former seems to represent the incentives and process the magnitude of reward, mediated by activity of the amygdala [78,79]. In addition to being part of the reward network, the caudate is also involved in processing negative affect [80]. It has been observed that both expert meditators and people who had received a mindfulness-based intervention showed lower activation of the caudate when presented with negative images [81,82]. This reduced reactivity to emotional signals or stimuli — both aversive and reward-related — could be taken to indicate an improvement in affective self-regulation [83].

The above evidence suggests that reduced caudate volume can be an index of the evolving brain [84,85] that promotes a more effective neural computation and enhances adaptive behavior [86]. In this regard, it should be noted that the participants were risk-taking individuals and that the N group showed an increased GMV of the caudate nucleus without having received any type of intervention. Several investigations have also found greater GMV in the caudate and other subcortical structures in risk-takers [87–90]. Thus, the fact that, regarding the control group, there was a reduction of GMV in the MT group may be a sign of neural plasticity and imply a recovery of the normal evolution of the structure. In addition, previous studies have reported that the improvement of certain cognitive processes after training is associated with a decrease in brain gray matter volume [91, 92]. We might thus speculate that a reduced caudate volume in the mindfulness group (compared with controls) may benefit the functioning of this structure and promote more efficient control and self-regulation mechanisms.

Deficits in functions that have been linked to the caudate nucleus, such as behavioral control and affect regulation, underlie urgent or impulsive behavior [12]. In this regard, our results show that the caudate volume was related to the BSI of positive urgency, finding that reductions in GMV in the MT group correlated with lower positive urgency. Positive urgency, defined as the tendency to act impulsively in response to intense positive emotions, implies a difficulty in suppressing prepotent responses [93] and is strongly related to risk behavior, such as driving errors and reckless driving [94,95]. The caudate has been implicated in impulsivity considered as urgency to respond, either negative or positive [93,96]. Similar to our results, Tschernegg et al. [97] observed that caudate volume correlated positively with impulsivity, independent of age in a delay discounting task. More specifically, Owens et al. [20] found a positive relationship between caudate GMV and positive urgency in a sample of pre-adolescents. The caudate has also shown increased activation when engaging in risky behavior [98]. Research in adolescents has found that bilateral activation was highly correlated with the decision to engage in risky choices, but more so in the presence than the absence of peers [98]. This structure is sensitive to feedback related to risky choices, as taking more risks is associated with increased bilateral caudate activity [99]. Therefore, the caudate plays an important role in the processing of affective stimuli (both rewarding and aversive), inhibitory control, risk-taking, and impulsive behavior, and is part of the cortico-striatal circuit comprising structures such as the anterior and posterior cingulate cortex, the insula, the amygdala, the striatum and the frontal and orbitofrontal cortices [17,69,100,101]. In this sense, alterations of the caudate have been related to various mental disorders whose main component is impulsivity, such as substance use and ADHD [102,103], and this structure could be an important component of the neural circuit of impulsivity, with excessive activity of this area being linked to rash behavior. Thus, if we consider the volume-activity relationship [104], our data suggests that the volume reduction in the MT group (compared with the control group) could be linked to reduced activity, which could in turn be associated with making fewer impulsive choices when acting under the influence of positive emotions. This could be applied to adapt mindfulness-based interventions to populations with high levels of impulsivity and emotion regulation difficulties.

However, more research is needed to confirm our findings. The quasi-randomization process may not have completely equalized the groups. Thus, complete randomized trials, with a greater number of participants, as well as study the long-term effects of the intervention are also needed to confirm that brain changes are maintained over time and are related to improved adaptive behavior.

In short, our results show that a mindfulness-based intervention produces changes in the structure of the caudate nucleus and improves dispositional mindfulness. In addition, reductions in caudate GMV in the MT group are related to lower positive urgency, and this impulsivity facet is associated with trait mindfulness. Therefore, it appears that a mindfulness-based intervention improves the skills of observing and non-reactivity to inner experience, while producing changes in the structure of the caudate nucleus. These structural changes are associated with a reduction in impulsivity levels, decreasing the tendency to act rashly in situations that generate positive emotions and thus facilitating more adaptive behavior.

Ethics approval

The Ethics Committee of Human Research of the University of Granada approved this research (204/CEIH/2016).

Consent to participate

Informed consent was obtained from all individual participants included in the study.

CRediT authorship contribution statement

Mas-Cuesta Laura: Funding acquisition, Investigation, Writing – original draft. **Baltruschat Sabina:** Conceptualization, Investigation, Writing – review & editing. **Cándido Antonio:** Conceptualization, Writing – review & editing. **Verdejo-Lucas Carmen:** Resources, Writing – review & editing. **Catena-Verdejo Elvira:** Resources, Writing – review & editing. **Catena Andrés:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data Availability

The authors do not have permission to share data.

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