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ORIGINAL ARTICLE

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Neural basis underlying the association between thought control ability and happiness: The moderating role of the amygdala

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Abstract

Thought control ability (TCA) plays an important role in individuals' health and happiness. Previous studies demonstrated that TCA was closely conceptually associated with happiness. However, empirical research supporting this relationship was limited. In addition, the neural basis underlying TCA and how this neural basis influences the relationship between TCA and happiness remain unexplored. In the present study, the voxel-based morphometry (VBM) method was adopted to investigate the neuroanatomical basis of TCA in 314 healthy subjects. The behavioral results revealed a significant positive association between TCA and happiness. On the neural level, there was a significant negative correlation between TCA and the gray matter density (GMD) of the bilateral amygdala. Split-half validation analysis revealed similar results, further confirming the stability of the VBM analysis findings. Furthermore, gray matter covariance network and graph theoretical analyses showed positive association between TCA and both the node degree and node strength of the amygdala. Moderation analysis revealed that the GMD of the amygdala moderated the relationship between TCA and happiness. Specifically, the positive association between TCA and self-perceived happiness was stronger in subjects with a lower GMD of the amygdala. The present study indicated the neural basis underlying the association between TCA and happiness and offered a method of improving individual well-being.

KEYWORDS
amygdala, gray matter density, happiness, structural covariance network, thought control ability

INTRODUCTION

People often have negative thoughts in daily life. These thoughts may be due to past memories (e.g., car accidents) or worries about future events (e.g., failure on the next exam). Previous studies have found that these intrusive negative thoughts affect people's cognitive function (Brewin & Smart, 2005; Pacheco et al., 2020) and emotion regulation ability (Zich et al., 2020) and further affect people's mental health (Arnáez et al., 2021; Brewin et al., 2010; Visser, 2020). Therefore, it is important for people to keep those negative and unwanted thoughts out of their minds, which refers to thought control ability (TCA). TCA is a reliable index of the ability to control or suppress intrusive and unwanted thoughts (Luciano et al., 2005; Williams et al., 2010). A number of studies have found that TCA is negatively associated with the symptoms of post-traumatic stress disorder (PTSD), depression, and anxiety as well as symptoms of other psychological disorders (Catarino et al., 2015; Feliu-Soler et al., 2019; Peterson et al., 2009). In general, previous studies have explored the relationship between TCA and negative emotions or mental disorders (Feliu-Soler et al., 2019; Gootjes & Rassin, 2014). However, few studies have investigated the association between TCA and positive emotions (Massar et al., 2020) or happiness.

Happiness has been defined as the sum of a person's recent levels of positive affect, high life satisfaction, and infrequent negative affect (Diener et al., 1999). Numerous studies have found that individuals with higher levels of self-perceived happiness are usually physically healthier, have longer lives and have more achievements in life (Diener & Seligman, 2002; Lyubomirsky et al., 2005; Steptoe et al., 2005). Therefore, it is crucial to identify factors that may increase happiness (Yang et al., 2021). Some researchers believe that intentional control of memory could be considered an adaptive emotional regulation strategy (Engen & Anderson, 2018), facilitating the retrieval of positive experiences and inducting the forgetting of other negative experiences, which can maintain individual subject well-being (Nørby, 2018). Moreover, taking into account emotions are an important part of happiness (Afzal et al., 2014; Humphrey et al., 2021); negative emotions are partly caused by retrieved negative memories or intrusive thoughts (Holland & Kensinger, 2010; Selby et al., 2008). Therefore, it is reasonable to infer that TCA may affect individual happiness. In addition, considering the negative relationship between TCA and mental illness (Feliu-Soler et al., 2019), it can be speculated that TCA may play an important role in improving happiness. However, no empirical studies have explored whether TCA is positively related to happiness or the neurobiological mechanism underlying this possible association.

In addition, not all individuals with high TCA will have a high level of happiness; it is essential to examine which factors moderate the association between TCA and happiness. Some studies have focused on the role of psychological and biological factors, including age, internal personality traits, inhibitory control ability, and emotional type of memory or thought (Anderson, 2005; Beadel et al., 2013; Depue et al., 2006; Erskine, 2004; Erskine et al., 2007). Among these factors, brain structure emerges as a crucial variable that significantly influences multiple behavioral relationships and can act as a moderator, regulating the strength of these relationships (Mander et al., 2017; Overfeld et al., 2020). Accumulating evidence from task-based functional magnetic resonance imaging (MRI) studies demonstrated that the amygdala played an important role in the representation and retrieval inhibition of emotional memory (Anderson et al., 2016; Daselaar et al., 2008; Engen & Anderson, 2018; Murty et al., 2011; Smith et al., 2006). Some studies have found that suppressing the retrieval of aversive images reduced amygdala activity (Depue et al., 2007; Depue et al., 2010). Critically, suppressing intrusions could also reduce emotional responses to suppressed images, and these dual effects on memory and emotion resulted from a common mechanism in the right prefrontal cortex that downregulated the hippocampus and amygdala in parallel (Gagnepain et al., 2017). Although functional MRI studies have advanced the understanding of the role of the amygdala in memory suppression, brain structure is the basis of brain function (Hermundstad et al., 2013), and no studies have explored the structural mechanism underlying TCA. This study firstly aimed to employ voxel-based morphometry (VBM) to explore the relationship between individual differences in TCA and the gray matter density (GMD) in the amygdala. VBM uses the voxel as the basic unit of analysis and compares each voxel of the human brain to identify structural differences that could partially account for individual differences in neural variability across cognitive functions, personality traits, and behaviors (Ashburner & Friston, 2000; Serra-Blasco et al., 2021; Uono et al., 2017). In contrast to functional connectivity and activation analyses, VBM is able to detect subtle structural changes in the human brain (Mechelli et al., 2005).

Moreover, the brain structural covariance network (SCN) presents an additional valuable approach to investigate the structural mechanisms, capturing correlated variations in the morphology of distinct brain regions within individuals (Griffiths et al., 2016; Seidlitz et al., 2018; Wannan et al., 2019). Compared with mere VBM analysis, SCN analysis provides a more comprehensive understanding of the brain's structural connectivity and functional relationships between regions (Chen et al., 2014; Coppen et al., 2016; Fermin et al., 2023). Previous studies have extensively investigated various morphological features, such as regional gray matter volume and density (de Schipper et al., 2017; Faridi et al., 2022; Soriano-Mas et al., 2013), cortical thickness (Kim et al., 2020), cortical surface area (Yun et al., 2020), and other related structural characteristics. Graph theoretical network analysis provides a valuable method for quantifying the organization of brain connectivity, representing the brain as graphs composed of nodes (representing regions or voxels) and edges (representing structural or functional connectivity among the nodes). Nodes exhibiting high structural degree and strength indicate regions of the brain that are highly interconnected and possess the capacity to engage in numerous functional interactions (Sporns, 2011). Alterations in gray matter SCN have been associated with individual sex and age (DuPre & Spreng, 2017; Montembeault et al., 2012; Shi et al., 2023), mental diseases (Coppen et al., 2016; Montembeault et al., 2016), social factors (Blumen & Verghese, 2019), and cognitive abilities (Ren et al., 2023; Shi et al., 2023; Simpson-Kent et al., 2021). Building on VBM, this study also utilized gray matter SCN to comprehensively explore the neural mechanisms of TCA from a network perspective.

More importantly, the GMD or gray matter volume of the amygdala has been linked to individual differences in preferences for processing emotional information (Marchewka et al., 2009; Ossewaarde et al., 2013; Richardson et al., 2004) and emotional regulation (Peng et al., 2019; Song et al., 2015). These factors may play a fundamental role in shaping emotional responses to negative memories and thoughts, potentially influencing the relationship between TCA and happiness (Gutiérrez-Cobo et al., 2021; Ng, 2016). On the one hand, it is essential to emphasize the role of the amygdala in memory consolidation (Hermans et al., 2014; Liu et al., 2016; McGaugh, 2018). When individuals encounter similar negative thoughts or memories, their emotional responses may diverge due to differences in their information processing preferences (Hamann & Canli, 2004; McGaugh, 2018). On the other hand, the amygdala plays a significant role in emotional regulation (Andrewes & Jenkins, 2019; Banks et al., 2007). Individuals with higher emotional regulation capabilities are better equipped to manage negative emotions stemming from negative thoughts, thereby reducing the impact on their happiness (Ma et al., 2020; Quoidbach et al., 2010; Quoidbach et al., 2015). Therefore, as a brain region associated with individual emotional information processing and emotional regulation, the amygdala may influence the positive effects of TCA on happiness. In other words, it is reasonable to hypothesize that the amygdala may moderate the relationship between TCA and happiness. Similarly, recent research has indicated that the amygdala's structure could moderate the association between negative experiences and emotions, such as childhood adversity and adult trait anger (d'Arbeloff et al., 2018), and early life stress and later trait anxiety (Kim et al., 2019).

In this study, we first explore the relationship between TCA and happiness. Previous studies have suggested that individuals with high levels of TCA are less vulnerable to psychological disorders (Catarino et al., 2015; Reynolds & Wells, 1999). We thus predicted that TCA would be positively correlated with happiness. Second, we tried to explore the correlation between individual differences in TCA and the GMD of the amygdala using the VBM analysis and SCN analysis. Finally, moderation analysis was performed to examine whether the GMD of the amygdala moderates the relationship between TCA and happiness.

METHOD

Participants

A total of 314 healthy college students (234 females; mean age = 19.41 ± 1.24 years) from Southwest University were recruited for this study, all of whom were right-handed native Chinese speakers without a history of neurological or psychiatric disorders. All participants also completed the Beck Depression Inventory (BDI-II) and the Beck Anxiety Inventory (BAI). The scores from BDI-II and BAI were employed as covariates to demonstrate the stability of our results. The experimental process was approved by the Brain Imaging Center of Southwest University. The study was reviewed for compliance with the standards for the ethical treatment of human participants and approved by the Ethical Committee for Scientific Research at Southwest University. All the participants provided informed consent prior to the experiment.

Behavioral measures

Thought Control Ability Questionnaire

The Thought Control Ability Questionnaire (TCAQ; Luciano et al., 2005) is a 25-item self-report inventory for assessing the level of TCA (e.g., "I think I am a person who can control positive and negative emotions well"). This scale has a unidimensional structure and is measured on a 5-point Likert scale ranging from 1 (*not at all*) to 5 (*totally suitable*) with a total score range from 25 to 100. The total score indicates an individual's ability to control unwanted thoughts, with higher scores suggesting higher TCA. The TCAQ showed high internal consistency and good test–retest reliability (Feliu-Soler et al., 2019; Luciano et al., 2005; Shi et al., 2021; Williams et al., 2010). In the present study, Cronbach's alpha for the total TCAQ score was .81.

Oxford Happiness Questionnaire

The Oxford Happiness Questionnaire (OHQ; Hills & Argyle, 2002) is a 29-item self-report inventory for assessing the level of happiness (e.g., "I often experience joy and elation"). This scale has a unidimensional structure and items are measured on a 6-point Likert scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*), with a total score ranging from 29 to 174. The total score indicates an individual's happiness level, with higher scores suggesting greater happiness. Previous research has demonstrated that this measure has good psychometric properties (Hills & Argyle, 2002; Kashdan, 2004). In the present study, Cronbach's alpha for the total OHQ score was .91.

MRI data acquisition and preprocessing

Image acquisition

The structural MRI data were scanned by a 3T Siemens-Trio Erlangen scanner (Siemens Medical Solutions) with a 12-channel head coil at the Brain Imaging Center of Southwest University. A magnetization-prepared rapid gradient echo (MPRAGE) sequence was used to collect each participant's high-resolution 3D T1-weighted anatomical images with the following parameters: 176 sagittal slices; repetition time = 1900 ms; echo time = 2.52 ms; inversion time = 900 ms; flip angle = 90°; resolution matrix = 256 × 256; voxel size = 1 × 1 × 1 mm^3; and slice thickness = 1.0 mm.

Preprocessing of structural data

The structural MRI data were processed using the SPM8 program (Wellcome Department of Cognitive Neurology; www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB 7.8 (MathWorks Inc.). First, each MR image was displayed in SPM8 to screen for artifacts and gross anatomical abnormalities. To improve registration, the reorientation of the images was manually set to the anterior commissure. Second, the images were segmented into gray matter (GM), white matter (WM), or other by using the new segmentation in SPM8. Then, we performed Diffeomorphic Anatomical Registration through Exponentiated Lie (DARTEL) algebra in SPM8 for registration, normalization, and modulation of the data (Ashburner, 2007). To ensure that regional differences in the absolute amount of GM were conserved, the image intensity of each voxel was modulated by the Jacobian determinants. Then, the registered images were transformed to Montreal Neurological Institute (MNI) space. Finally, the normalized modulated images of GM and WM were smoothed with an 8-mm full-width at half-maximum Gaussian kernel to increase their signal-to-noise ratio.

Statistical analysis

VBM analysis

Statistical analysis of the brain imaging data was performed with SPM12. In the whole-brain analysis, multiple regression analysis was used to explore the association between the GMD and individual differences in TCA. In the multiple linear regression analyses, the GMD of each voxel in the whole brain was included as the dependent variable, and the TCAQ score was included as the independent variable. To control for possible confounding variables, age, gender, and the global GMD were entered as covariates in the regression model (Kulynych et al., 1994; Peelle et al., 2012). To avoid edge effects around the borders between GM and WM, an absolute threshold masking of 0.2 was used; thus, voxels with GM values lower than 0.2 were excluded from the analyses (Ridgway et al., 2009; Wei et al., 2015).

Furthermore, small-volume correction (SVC) was performed in the areas with a strong a priori hypothesis. The regions of interest (ROIs) were chosen because previous structural and functional imaging studies revealed that the amygdala might play an important role in thought control (Depue et al., 2007; Depue et al., 2010; Gagnepain et al., 2017). The Wake Forest University (WFU) Pick Atlas (Maldjian et al., 2003) was used to define areas in the amygdala. Specific ROIs were examined at a corrected threshold of $p < .05$ using the familywise error (FWE) method for multiple comparisons.

Intra-individual gray matter SCN

In order to further complement the results of VBM, we delved into the relationship between the GMD of the amygdala and TCAQ from the perspective of structural networks. We generated 116 cortical and subcortical ROIs from the Automated Anatomical Labeling (AAL) 116 atlas. Subsequently, these AAL ROIs were resliced to the same dimension as the tissue segmented images obtained during the VBM preprocessing step. These resliced ROIs were then utilized to mask the individual modulated, normalized GM images, and we extracted the average density within each ROI using the REX toolbox.

GMD of all 116 anatomical regions for each individual were z-score transformed using the mean and standard deviation values calculated from all subjects within each ROI. Finally, a measure of joint variation (which is not the same as the classical statistical definition of covariance) between the 116 regions represented the edge-weights (distributed between 0 and 1) of the network and was calculated using the following formula (Liu et al., 2021; Yun et al., 2020):

$$\begin{aligned}&[\text{The gray matter covariance between the } i\text{th}(\text{for } i=1-116) \text{ and } j\text{th}(\text{for } j=1-116)\text{ROI in the } s\text{th}(\text{for } s=1-314) \text{ participant}]\\&\quad=1/\exp\{[(\text{z transformed value of } i\text{th ROI in } s\text{th participant})-(\text{z transformed value of } j\text{th ROI in } s\text{th participant})]^2\}.\end{aligned}$$

Graph theoretical analyses

For each of the individual SCNs, a series of graphs was constructed and analyzed over a range of connection densities from 0.1 to 0.5 with an interval of 0.1. For instance, when applying a density threshold of $K = 0.1$, the edge weights in the network were sorted into numerical order, and only the strongest 10% of edges were retained.

At each of these thresholds, we calculated the node degree and node strength of bilateral amygdala. The node degree represents the number of connections that a node has with the rest of the network (Romero-Garcia et al., 2018), while node strength represents the sum of edge weights connecting a node to other nodes within the network (Prasad et al., 2022).

Partial correlation analysis

Spearman partial correlation analysis was performed to examine the correlation between TCAQ scores and network measures, including the node degree and node strength of bilateral amygdala at different threshold levels, corrected for age, sex, and global GMD.

Moderation analysis

A moderator variable is a variable that may influence the direction and/or strength of the relationship between an independent variable and a dependent variable (Baron & Kenny, 1986). Moderation studies can address "when" or "whom" questions regarding variation in the strength of the relationship between X and Y. To study whether the relationship between TCA and happiness was affected by the GMD of the bilateral amygdala, we performed a moderation analysis (Holmbeck, 2002) using the Johnson–Neyman method via the Process procedure in SPSS 22.0 (Hayes, 2017). These methods have been successfully employed in previous studies (Kaller et al., 2012; Maier et al., 2020; Simon et al., 2020; Wei et al., 2015; Yao et al., 2018). In this moderation analysis, age, gender, and global GMD were included as covariates. To generate 95% confidence interval (CI), 5000 bootstrapped samples were drawn. Simple slope analysis was used to determine the associations between TCA and happiness at low (mean − 1 *SD*) and high (mean + 1 *SD*) levels of the GMD of the amygdala.

RESULTS

Behavioral results

To mitigate potential bias arising from shared method variance, the questionnaires with good reliability and validity were used as the measuring instruments. During the testing process, special attention was given to maintaining result confidentiality, and we used the reverse scoring method for specific questionnaire items.

To examine the presence of common method biases, the Harman's Single Factor Test was performed in SPSS 22.0 (Harman, 1976; Podsakoff et al., 2003; Tehseen et al., 2017). The Harman's Single Factor Test is performed through an exploratory factor analysis, where the researchers usually examine whether the first extracted factor accounts for more than 40 percent of the total variance (Aguirre-Urreta & Hu, 2019; Elahi et al., 2020; Fuller et al., 2016). The results of the exploratory factor analysis indicated that the number of factors without rotation exceeded 1, and the variance explained by the first principal component was 23.648%, which fell below the threshold of 40%. Overall, it can be inferred that the measurement did not exhibit significant common method bias.

Table 1 provides the descriptive statistics of all subjects' demographic and behavioral measurements. The Pearson correlation analysis including age and gender as covariates revealed that participants' level of happiness was positively correlated with their TCA ($r_{310} = 0.506$, $p < .001$). Participants who had a stronger ability to control their unwanted thoughts reported higher happiness levels.

VBM results

The TCAQ scores were negatively correlated with the GMD in two clusters that mainly included areas in the bilateral amygdala (left: cluster size = 87 voxel, $t = 3.93$, $p_{(\text{corr})} < .05$; right: cluster size = 22 voxel, $t = 3.58$, $p_{(\text{corr})} < .05$; Figures 1 and 2 and Table 2). Age, gender, and global GMD were included as covariates in all analyses. To provide a more comprehensive understanding of the neural mechanisms underlying TCA, the results of whole-brain analyses were also reported (Table S1). TCAQ scores were positively correlated with GMD predominantly involving fusiform, precuneus, parahippocampal gyrus, medial frontal gyrus, and thalamus, and were negatively correlated with GMD in several brain areas, including temporal gyrus, amygdala, anterior cingulate, postcentral gyrus, insula and middle occipital gyrus at an uncorrected threshold ($p < .001$) with 20 extend threshold.

Additionally, we conducted a cross-validation of the VBM results using two subsets: the training samples and the test samples, each consisting of 157 participants with balanced gender and age distributions. Similar VBM analyses were conducted on the training samples; we consistently observed a stable negative correlation between the GMD of the amygdala and TCAQ scores in all 10 iterations of the analysis; and ROIs where GMD significantly correlated with TCAQ scores in the training samples were used as masks to extract GMD in the test samples. Partial correlation analyses showed a stable negative correlation between the GMD of amygdala and TCAQ scores in the training samples controlling for gender, age, and global GMD across 10 iterations. In the test samples, the correlation consistently showed a negative relationship with occasional significant results. For more detailed information, please refer to the supplementary material (Results of cross-validate analyses, Figure S1).

TABLE 1 Demographic and psychometric measurements ($N = 314$)

Item	*M*	*SD*	Minimum	Maximum
Age	19.41	1.24	17	25
TCAQ	77.43	12.13	46	116
OHQ	116.57	15.66	67	160

Abbreviations: OHQ, Oxford Happiness Questionnaire; TCAQ, Thought Control Ability Questionnaire.

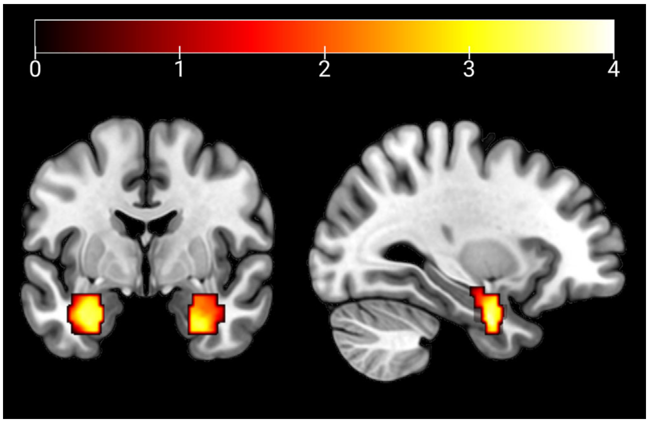


FIGURE 1 Region of interest voxel-based morphometry analysis of gray matter density (GMD) in the bilateral amygdala. Red-yellow shows voxels demonstrating significant association between GMD and reduced Thought Control Ability Questionnaire (TCAQ) scores after controlling for age, gender, and global GMD. The background image is the MNI152 standard space T1 template. The number in the color bar represents the T value.

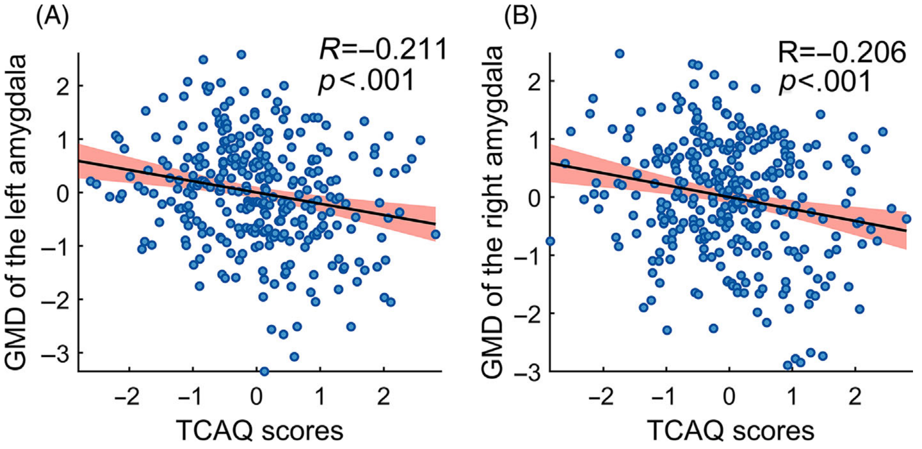


FIGURE 2 Regional gray matter density (GMD) was negatively correlated with Thought Control Ability Questionnaire (TCAQ) scores. Scatter plot of the correlation between TCAQ scores and the GMD of the (A) left and (B) right amygdala after regressing out age, gender, and global GMD. Both dimensions were Fisher Z-transformed for analysis and display. In the scatter plot, the red shaded areas represent 95% CIs.

TABLE 2 Regional gray matter density showed significant correlations with reduced TCAQ scores.

	Peak MNI coordinate				
Region	***x***	***y***	***z***	**Peak T-values**	**Cluster size (voxel)**
Amygdala (L)	−23	−5	−21	3.93	87
Amygdala (R)	21	−3	−24	3.58	22

Note: Results are $p_{(FWE)} < .05$, corrected for multiple comparisons at a cluster level with small-volume correction, with an underlying voxel level of $p < .001$, uncorrected.
Abbreviations: L, left; R, right; TCAQ, Thought Control Ability Questionnaire.

TABLE 3 The correlation between TCAQ scores and the node degree and node strength of the bilateral amygdala ($K = 0.3$)

ROIs	**Node degree**	**Node strength**
Amygdala (L)	0.195 ($p < .001$)	0.185 ($p < .010$)
Amygdala (R)	0.109 ($p = .054$)	0.111 ($p = .051$)

Abbreviations: L, left; R, right; ROIs, regions of interest; TCAQ, Thought Control Ability Questionnaire.

Relationship between TCAQ scores and network measures

Among the various network density levels of $K = 0.1$–0.5 (with density interval of 0.1), partial correlation analysis showed the best results with a density threshold of $K = 0.3$. Specifically, TCAQ scores displayed a significant positive correlation with both the node degree and node strength of the left amygdala. Additionally, there was a marginal significance observed in the correlation between TCAQ scores and both the node degree and node strength of the right amygdala (Table 3). These findings were mainly consistent when considering different values of K, as reported in the supplementary material (Results of TCAQ scores and network measures, Figure S2).

Moderation analysis

As mentioned above, this study observed a significant positive correlation between TCA and the levels of happiness. Furthermore, the GMD of the bilateral amygdala was negatively associated with the TCA. Next, we analyzed whether individual differences in the GMD of the amygdala moderated the relationship between TCA and happiness. The results showed that the GMD of the amygdala (bilateral) moderated the relationship between TCA and happiness. There was a significant interaction between TCAQ scores and the GMD of the bilateral amygdala, following the mean-centering of both TCAQ scores and the GMD (Table 4; for the left amygdala: $\Delta R^2 = .295$, $\beta = -12.474$, $t = -2.748$, $p = .006$; for the right amygdala: $\Delta R^2 = .302$, $\beta = -20.202$, $t = -3.174$, $p < .001$). The positive relationship between TCAQ scores and OHQ scores was significantly stronger in participants with a lower GMD of the bilateral amygdala than in participants with a higher GMD (Figure 3).

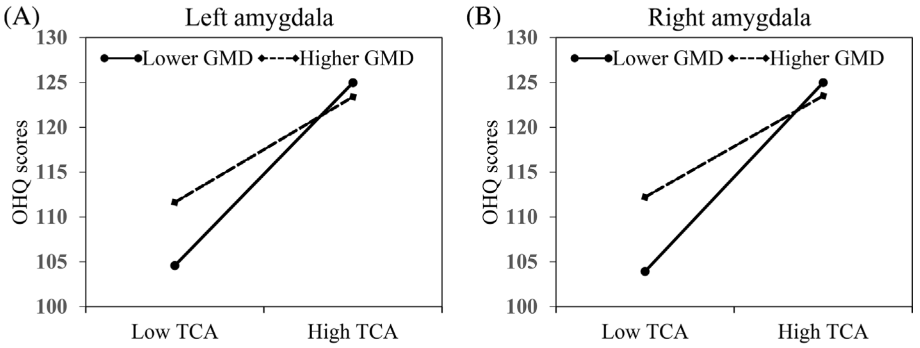
Supplementary analyses

Previous studies have shown that individual levels of anxiety and depression are closely related to TCA and happiness

TABLE 4 Results of the moderated regression analysis to predict happiness.

Variable	β	*SE*	*t*	R^2
Left amygdala				.295***
Gender	3.748	1.753	2.138*	
Age	0.799	0.619	1.291	
Global GMD	0.001	0.001	0.321	
TCA	0.663	0.065	10.273***	
Left amygdala	95.937	68.366	1.403	
TCA × Left amygdala	−12.474	4.539	−2.748**	
Right amygdala				.302***
Gender	3.184	1.769	1.800	
Age	0.728	0.616	1.182	
Global GMD	0.001	0.001	0.110	
TCA	0.667	0.064	10.411***	
Right amygdala	170.987	103.873	1.646	
TCA × Right amygdala	−20.202	6.365	−3.174***	

Note: The independent variable is the Oxford Happiness Questionnaire score.
Abbreviations: GMD, gray matter density; TCA, thought control ability.
*$p < .05$; **$p < .01$; ***$p < .001$.



Lower: simple slope, b= .841, t=9.553, p< .001
Higher: simple slope, b= .485, t=5.122, p< .001

Lower: simple slope, b= .868, t=9.881, p< .001
Higher: simple slope, b= .466, t=5.044, p< .001

FIGURE 3 The gray matter density (GMD) of the (A) left and (B) right amygdala moderated the relationship between thought control ability (TCA; Thought Control Ability Questionnaire [TCAQ] scores) and happiness (Oxford Happiness Questionnaire scores). Simple slopes are plotted at low (mean − 1 *SD*) and high (mean + 1 *SD*) GMD of the left and right amygdala.

(Feliu-Soler et al., 2019; Wasil et al., 2021). In order to exclude the influence of confounding variables, the supplementary analysis also controlled the individual's anxiety (as measured by BAI) and depression (as measured by BDI-II). Both behavioral and neural results remained largely unchanged when anxiety and depression were controlled. TCA was still significantly associated with happiness ($r = 0.409$, $p < .001$) and the GMD in bilateral amygdala (the left amygdala: $r = -0.196$, $p = .001$; the right amygdala: $r = -0.186$, $p = .001$). More importantly, the moderating effect of the GMD of the bilateral amygdala was still significant for the association between TCA and happiness (for the left amygdala: $\Delta R^2 = .349$, $\beta = -13.867$, $t = -3.148$, $p < .001$; for the right amygdala: $\Delta R^2 = .351$, $\beta = -19.864$, $t = -3.224$, $p < .001$).

DISCUSSION

The present research explored the neurobehavioral relationship between the levels of happiness and the ability to control unwanted thoughts. As predicted, the results confirmed that TCA was positively associated with levels of self-perceived happiness. Moreover, TCA was negatively associated with the GMD of the bilateral amygdala, which was affirmed by spilt-half validation. Furthermore, gray matter covariance network and graph theoretical analyses revealed a positive link between TCA and the amygdala's node degree and node strength. More importantly, the GMD of the bilateral amygdala moderated the relationship between TCA and happiness. Specifically, higher happiness levels were associated with higher TCA in individuals with a lower GMD of the bilateral amygdala.

In other words, the influence of TCA on happiness was significantly stronger in participants with a lower GMD of the bilateral amygdala.

The behavioral results showed that happiness was positively associated with TCA. First, TCA helps individuals alleviate negative emotions, thereby increasing happiness. Previous studies have found that individuals with higher TCA reported fewer intrusions of negative memories (Küpper et al., 2014; Streb et al., 2016) and had less severe symptoms of depression after experiencing negative life events (Lu et al., 2021). Furthermore, previous studies have also found that sustained attention to or "rumination" about negative experiences contributes to present unhappiness (Nolen-Hoeksema, 1991), depression (mainly characterized by rumination of the past), and anxiety (mainly characterized by worry about the future; Roley et al., 2015; Snyder & Hankin, 2016). Moreover, lower levels of subjective well-being were accompanied by higher rumination (Elliott & Coker, 2008; Weber & Hagmayer, 2018). In contrast to rumination, when unpleasant thoughts arise, people can actively and deliberately exclude them from awareness (Anderson & Green, 2001; Anderson & Hanslmayr, 2014). The selective suppression of negative thoughts and memories could further reduce psychological conflict (Hu et al., 2015), contribute to efficient cognition (Anderson & Hulbert, 2021; Fawcett & Hulbert, 2020), and preserve mental health (Costanzi et al., 2021; Gagnepain et al., 2017; Hu et al., 2017). Second, TCA was also associated with positive emotions and contributed to emotion regulation (Engen & Anderson, 2018; Gagnepain et al., 2017), maintenance of focus and cognitive flexibility during tasks (Fawcett & Hulbert, 2020; Van Vugt et al., 2018), maintenance of positive self-perception (Elliott et al., 2021) and self-image (Fawcett & Hulbert, 2020), strengthening of beliefs and attitudes (Waldum & Sahakyan, 2012), and improvement of resilience (Shi et al., 2021). These factors help generate more positive emotions, which are essential parts of happiness (Cohn et al., 2009). Third, in addition to positive and negative emotions, life satisfaction was also strongly correlated with happiness (Bieda et al., 2019; Selim, 2008). Recent studies have found that TCA has a positive relationship with life satisfaction (Williams et al., 2021) and momentary affect (Massar et al., 2020). Finally, Nørby (2018) suggested that selective forgetting may help maintain well-being. The present study experimentally determined a positive correlation between TCA and happiness.

The current study uncovered a negative correlation between variations in the GMD of the amygdala and individual differences in TCA. From the standpoint of cognitive control and memory suppression, individuals with higher TCA demonstrate superior capabilities in suppressing negative thoughts (Feliu-Soler et al., 2019; Luciano et al., 2005). Utilizing with the Think/No-Think (TNT) task (Anderson & Green, 2001), many functional MRI studies have indicated that suppressing unpleasant reminders or images leads to a reduction in amygdala activation (Depue et al., 2007; Depue et al., 2010; Gagnepain et al., 2017). The repeated activation of a brain region leads to an increase in the GM of that region (Draganski et al., 2004; Granert et al., 2011; Ilg et al., 2008), whereas inhibition leads to a decrease in the GM of that region (Depue & Banich, 2012; Takeuchi et al., 2012). It is reasonable to hypothesize that inhibiting the retrieval of negative thoughts, facilitated by higher TCA, may be associated with reduced amygdala activation and a decrease in the GMD of the amygdala. Moreover, a decrease in GMD of the amygdala has been reported following mindfulness training (Hölzel et al., 2010), which is also a beneficial strategy for coping with intrusive thoughts (Emerson et al., 2018; Shipherd & Fordiani, 2015) and improving inhibitory control (López-Navarro et al., 2020; Pozuelos et al., 2019). Future longitudinal research is necessary to investigate the causal impact of thought control training on changes in brain structure.

Moreover, the findings of brain SCN and graph theoretical analyses consistently showed a positive correlation between TCAQ scores and both the node degree and node strength of the amygdala. It was consistent with previous research indicating the amygdala's role in emotional processing, memory control, and affective responses (Cotton et al., 2020; Harnett et al., 2022; Roos et al., 2017). Previous studies have reported reduced measures of centrality, segregation, and integration in nodes within the left amygdala in patients with major depressive disorder compared to healthy individuals (Zhang et al., 2022). In addition, lower amygdala degree centrality has been observed in the offspring of mothers with higher stress during pregnancy (Mareckova et al., 2022). The finding suggested that individuals with higher TCA have stronger structural similarities between the amygdala and other brain regions, suggesting a potential enhanced ability to process unwanted thoughts and memories. Overall, it further confirmed the important role of the amygdala in the ability of thought control.

The current findings also indicated that the positive relationship between TCA and happiness was moderated by the GMD of the bilateral amygdala. Emotion regulation theory underscores the amygdala's role in emotion processing (Hrybouski et al., 2016; Sergerie et al., 2008; Šimić et al., 2021) and emotion regulation (Berkman & Lieberman, 2009; Eden et al., 2015). A recent functional MRI-based neurofeedback study revealed a negative correlation between changes in TCA and practice-related alterations in the functional connectivity of the prefrontal cortex and amygdala during emotional regulation (Zich et al., 2020). This finding aligns with the present research, suggesting that the amygdala is involved in individual emotional information processing and emotional regulation and interacts with TCA to affect happiness.

More precisely, individuals with lower GMD of the amygdala may be more likely to experience an improvement in happiness through increased TCA. Enlargement of the bilateral amygdala is identified as a risk factor for mental health and happiness. Increased GM volumes of the amygdala have been reported in many affective disorders (Kovacevic et al., 2021; Qin et al., 2014; Vassilopoulou et al., 2013). Greater GMD of the amygdala was also observed in trauma-exposed survivors who underwent more stressful events (Li et al., 2017).

Importantly, some studies have demonstrated a reduction in perceived stress due to mindfulness training, correlating positively with a decrease in the GMD of the right basolateral amygdala (Hölzel et al., 2010) and reduction in amygdala volume (Kral et al., 2022; Savic, 2015). Therefore, it is conceivable that a lower GMD of the amygdala may assist individuals in more effectively regulating their emotions, alleviating the impact of stress events through thought control training, and subsequently enhancing their happiness.

Numerous studies have consistently shown a link between TCA deficiency and various psychological disorders and clinical symptoms, including anxiety, depression, PTSD, and obsessive–compulsive symptoms (Catarino et al., 2015; Feliu-Soler et al., 2019; Morillo et al., 2007; Moulding & Kyrios, 2006). Similarly, larger GM density or volume of the amygdala has been found in individuals with depression and anxiety (Machado-de-Sousa et al., 2014; Vassilopoulou et al., 2013). Hence, it is reasonable to speculate that a close association between the amygdala and TCA may also be observed in clinical samples. In addition, task-based research has demonstrated that compared to controls, individuals with major depressive disorder exhibited distinct patterns of activity in the amygdala and hippocampus during memory suppression involving negative valence stimuli (Sacchet et al., 2017). Future studies could further explore the neural mechanisms of TCA in clinical samples, shedding more light on its implications for psychological disorders and their treatment.

There are several limitations to the present study. First, the present findings are limited to the instrument used to assess TCA. Specifically, we used a self-report questionnaire to measure TCA. Self-report data reflect a range of cognitive biases, such as overestimation (the Kruger–Dunning effect; Kanai & Rees, 2011). Future studies should use laboratory procedures, similar to the directed forgetting paradigm and TNT task, to explore the relationship between TCA and happiness. Second, the sample size in this study was relatively small and consisted of highly educated, healthy, and young adults. Therefore, the observed associations should be evaluated in future studies with larger and more diverse samples. Third, the study utilized a cross-sectional design and employed correlational analyses, limiting the ability to establish causal relationships and control for potential confounding variables. Future researchers can conduct experimental or longitudinal studies to explore the influence of TCA and its neural mechanisms on happiness.

CONCLUSION

The present study used VBM to explore the neurobehavioral relationship between TCA and happiness. This study demonstrated that TCA was positively associated with happiness, which explains why people who find it easier to let go of negative thoughts can achieve greater happiness. VBM analysis revealed the structural basis of TCA. Specifically, TCA was negatively associated with the GMD of the bilateral amygdala, and the split-half validation analysis showed consistent results, further confirming the stability of the VBM analysis findings. Furthermore, TCA was also positively related to both node degree and node strength of the amygdala in the gray matter covariance network. Notably, the GMD of the amygdala played an important role in improving the relationship between TCA and happiness. In general, this research found that the ability to control negative thoughts is important for happiness and mental health and indicated a way to improve individual happiness.

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CONFLICT OF INTEREST STATEMENT

The authors have declared that there are no competing interests.

ETHICS STATEMENT

The study was reviewed for compliance with the standards for the ethical treatment of human participants and approved by the Ethical Committee for Scientific Research at Southwest University. All the participants provided informed consent prior to the experiment.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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