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Reduced feelings of regret and enhanced fronto-striatal connectivity in elders with long-term Tai Chi experience

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Abstract

The current study investigates how long-term Tai Chi experience affects the neural and emotional response to regret in elders. Participants perform the sequential risk-taking task while undergoing functional magnetic resonance imaging (fMRI) scanning. In the task, participants opened a series of boxes consecutively and decided when to stop. Each box contained a reward, except for one which contained a devil. If the devil was revealed, then this served to zero the participant's gain in that trial. Once stopped, participant's gains and missed chances were revealed. Behaviorally, the Tai Chi group showed less regret, reduced risk taking, higher levels of nonjudgment of inner experience and less emotional sensitivity to outcome. fMRI results showed that the Tai Chi group demonstrated stronger fronto-striatal functional connectivity in trials with numerous missed chances. The nonjudgment of inner experience mediated the impact of fronto-striatal functional connectivity on Tai Chi practitioners' emotional sensitivity to outcome. These results highlight that long-term Tai Chi exercise may be effective in alleviating feelings of regret in elders by promoting reduced judgment of inner experience and enhanced emotion regulation through the strengthening of fronto-striatal functional connectivity.

Key words: Tai Chi; meditation; regret; striatum; functional connectivity

Introduction

Successful aging is an increasing global concern. Depression is prevalent amongst the elders (Rajkumar *et al.*, 2009), and can have a marked impact upon quality of life (Blazer *et al.*, 1991). The cognitive model of depression causally associates it with rumination (Roelofs *et al.*, 2008a, 2008b), which incorporates

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repetitive, negative, and self-focused thoughts about the past or future (Thomsen, 2006). For example, the relation between rumination and depression was demonstrated in a case-control study which found that elders with depression had increased rumination of negative stimuli relative to healthy controls (Devanand *et al.*, 2002). A reduced capacity to disengage from ruminative thought might be related to a deficit in executive functions, such deficits are widely reported among elders with depression (Blazer *et al.*, 1991; Hays *et al.*, 1997). In addition, rumination is also associated with counterfactual thinking (Spellman and Mandel, 2010; Epstude and Roese, 2017), the comparison between 'what is' and 'what might have been' (Roese, 1994, 1997). Regret, a common negative emotion in daily life, results from the upward counterfactual thinking, i.e. the comparison between 'what is' and the better 'what might have been' (Coricelli *et al.*, 2005; Sommer *et al.*, 2009; Coricelli and Rustichini, 2010). Numerous studies have found that being immersed in regret was harmful to mental health and even could induce mental illness (Markman and Miller, 2006; Chase *et al.*, 2010; Markman and Weary, 2011). For instance, Roese *et al.* (2009) revealed that regret was associated with late life depression and had a marked negative impact upon quality of life. Moreover, Brassen *et al.* (2012) found that unsuccessfully aged (i.e. late-life depressed) individuals reported more regret when presented with poor outcomes compared with successfully aged (healthy) individuals. So, intense regret resulting from uncontrollable counterfactual thinking or automatic rumination might therefore be an obstacle to mental health in later life. Accordingly, how to modulate and reduce elders' regret is widely concerned by researchers.

To control regret by reducing rumination might be an effective way to maintain good mental health for older adults. A practical method to lessen rumination is to promote nonjudging, a nonevaluative stance toward inner experiences, which has been identified as a key component of meditation (Teasdale *et al.*, 1995; Coffey *et al.*, 2010). Meditation is associated with increased levels of nonjudging and associated drops in rumination (Jain *et al.*, 2007; Deyo *et al.*, 2009). Long-term meditation training can help individuals to break their habitual ruminative cycle by making them aware of their feelings and thoughts without judging them or getting trapped in them (Roelofs *et al.*, 2008b). Neuroimaging studies show differential brain activation patterns after long-term or short-term meditation training. Novice meditators (short-term meditation training) showed increased activity in prefrontal areas involved in executive processing (Allen *et al.*, 2012; Lutz *et al.*, 2014). For example, Allen *et al.* (2012) revealed greater prefrontal activation during executive processing within an emotional Stroop task in healthy individuals after 6 weeks of meditation training. Meanwhile, experienced meditators (long-term meditation training) displayed diminished activation in prefrontal regions (Grant *et al.*, 2011; Taylor *et al.*, 2011; Gard *et al.*, 2012). In regard to the different brain activation patterns between novice meditators and experienced meditators, previous studies interpreted this as novice meditators needing to overcome habitual ways of internally reacting to one's own emotions and might therefore show greater prefrontal activation. But for experienced meditators, they might have automated an accepting stance toward their experience (Tang *et al.*, 2015). Thus long-term meditation training may help to suppress regret automatically by improving the ability to not-judge one's own inner experience.

Meditation encompasses a family of complex practices that include mindfulness meditation, yoga, Tai Chi and chi gong. Of these practices, Tai Chi is a popular exercise for older adults in China which combines Chinese martial arts and meditative movements with a kind of yogic relaxation through deep breathing (Sandlund and Norlander, 2000; Wang *et al.*, 2014; Wayne *et al.*, 2014). Compared with other exercises that contain meditation element, Tai Chi is generally recognized as a safe and low-cost complementary therapy and has been proven to improve balance and reduce fall risk in healthy and neurologically impaired older adults (Li *et al.*, 2012; Manor *et al.*, 2013). It has been claimed that Tai Chi connects the mind and the body by incorporating physical, cognitive, social and meditative components in the same activity (Wayne *et al.*, 2017). Previous studies revealed that Tai Chi, as a physical exercise, was an effective method to not only improve health fitness, such as neuromuscular functions, cardiorespiratory system and balance control (Ray *et al.*, 2005), but also to enhance psychological well-being for older adults (Wang *et al.*, 2010).

However, to the best of our knowledge, there is no research in the literature explores the relationship between Tai Chi practice and regret. To fill this gap, the current study (containing a Tai Chi group and a control group) aimed to investigate whether long-term Tai Chi practice is associated with enhanced nonjudgment of inner experience and reduced automatic feelings of regret. We used the sequential risk-taking task which has been shown to beeffective in inducing regret (Brassen *et al.*, 2012; Liu *et al.*, 2016 2017; Li *et al.*, 2018). During the task, participants were asked to open a series of boxes consecutively until they decided to stop. Each box contained a reward (gold), except for one that contained an adverse stimulus (devil), which caused the participant to lose all the gold collected in that trial. By using this sequential risk-taking task, researchers found that striatum participated in the processing of regret (Liu *et al.*, 2016, 2017; Li *et al.*, 2018). Specially, Brassen *et al.* (2012) found that compared with older adults with depression, successful aging showed reduced responsiveness to regret paralleled by autonomic and fronto-striatal characteristics indicating adaptive shifts in emotion regulation. There exists strong anatomical connectivity between striatum and frontal region (Alexander *et al.*, 1986), and the functional connectivity between these brain regions are thought to play a key role in emotion regulation (Ochsner and Gross, 2005; Wager *et al.*, 2008; Lozoff, 2011). For instance, poor emotion regulation observed in depression has been associated with reduced frontal-striatal connectivity (Heller *et al.*, 2009). In the present study, we were interested in whether long-term Tai Chi practice could enhance emotion regulation by improving frontal-striatal connectivity, with a specific focus on regret.

The main focus of current study was to examine the nonjudgment of inner experience and regret in older adults with long-term Tai Chi practice by using the sequential risk-taking task. Behaviorally, we predicted that the Tai Chi group would show greater nonjudgment of inner experience and less regret than the control group. Furthermore, we hypothesized that nonjudgment of inner experience would be associated with reduced emotional sensitivity to outcome in Tai Chi group. At the neural level, in line with previous findings, we predicted striatum would participate in the processing of regret and that the Tai Chi group would show diminished activation in frontal areas when the outcome of a given trial was revealed. Finally, we predicted that the Tai Chi group would show stronger fronto-striatal connectivity relative to the control group and that in the Tai Chi group, increased fronto-striatal connectivity would explain variation in nonjudgment of inner experience.

Experimental procedures

Participants

Thirty-one Tai Chi practitioners (21 female, aged from 60 to 70, $M = 64.93$, s.d. = 2.37) and 31 control participants (21 female, aged from 60 to 70, $M = 64.06$, s.d. = 3.05) participated in the experiment. Tai Chi participants had taken Tai Chi exercise for an average of 9.98 ± 5.16 years. Control participants were active with other types of physical exercise without a meditation component, such as jogging, swimming and public square dancing. All of the participants (i) were right-hand, (ii) were with normal or corrected-to-normal vision, (iii) had the ability to provide written informed consent and (iv) did not have any neurological disease, history of stroke or severe cerebrovascular disease. Four Tai Chi participants and five control participants were excluded due to severe head motion (>3 mm or 3°). Only the remaining 27 Tai Chi participants (17 female, aged from 60 to 70, Mean (M) = 65.07, Standard Deviation (s.d.) = 2.24) and 26 control participants (16 female, aged from 60 to 70, $M = 64.15$, s.d. = 3.05) were included in fMRI data analyses. Moreover, five Tai Chi participants (one with severe head motion) and five control participants (four with severe head motion) were excluded in the analysis about meditation due to missed data from the Five Facet Mindfulness Questionnaire (FFMQ). All participants gave informed consent before scanning. The study was approved by the Ethics Committee on Human Experiments of East China Normal University.

Procedure

Psychological measures

Before the task, to match the Tai Chi and control groups on depression degree, impulsiveness level and other factors, participants were required to fill out the Chinese version of the Beck Depression Inventory-II (BDI-II) (Beck et al., 1996), Barratt Impulsiveness Scale-11th (BIS-11th) (Patton et al., 1995) and NEO Five-Factor Inventory (Costa and McCrae, 1992). Moreover, to investigate the difference of meditation level between two groups, we also measured FFMQ (Baer et al., 2006) and Mindful Attention Awareness Scale (MAAS) (Brown and Ryan, 2003) (see Supplementary Material for details).

Experimental paradigm

The participants were recruited by the experimental assistant to avoid any contamination derived from the experimenter's knowledge or expectation. Before scanning, participants were told that they would play a sequential decision task while undergoing fMRI scanning. They were also informed that they would obtain tokens ('gold coins') from the task and that the payment for their participation was determined by their total number of coins obtained from the task (1 coin for 1 Chinese Yuan).

All participants completed 80 trials in the scanner. On each trial, an array of eight boxes was presented, where seven boxes contained gold coins and one box contained a devil. The position of the devil was set randomly on each trial. Boxes were opened from left to right. At any stage, participants had 2000 ms to make a key press to indicate whether they wanted to either open the next box or stop and collect the gains acquired so far in that trial. Opening the box with the devil ended the current trial, and all gains from that trial were lost. If participants stopped and collected their gains, the actual position of the devil was revealed, thus informing participants about both the number of gold coins they gained and the number of gold coins they had missed. A jittered interval (ranging from 1800 to 2250 ms) was presented either after the participant decided to stop or after unpacking the devil. Next, the outcome was presented for 3000 ms. This was highlighted on the screen by a cyan square (in the case of stopping and collecting the gains) or by a red square (in the case of unpacking the devil and losing the gains in that trial). The outcome of each trial might be one of the following two condition: (i) Gain condition, in which participants did not unpack the devil and gained gold coins in that trial, (ii) Loss condition, in which participants unpacked the devil and lost the gold coins collected in that trial. Another jittered interval (ranging from 1500 to 2500 ms) was presented after the outcome stage. Then, the emotional rating stage was presented. At this stage, participants were asked to rate how they felt about their choice on a 9-point scale from extreme regret (defined as -4) to extreme relief (defined as 4) in 3000 ms. Finally, an additional jittered intertrial interval (ranging from 1500 ms to 15 500 ms) was introduced. Figure 1 displays two of the possible outcome conditions for a trial.

Structural and functional MRI data acquisition

Scanning was carried out on a 3T Siemens Trio system at the Functional MRI Lab (East China Normal University, Shanghai). For functional images, 35 slices were acquired using a gradient-echo echo-planar imaging (EPI) sequence (TR = 2000 ms, TE = 30 ms, FOV = 220 mm, matrix size = 64×64, slice thickness = 4 mm). Before the functional run, a high-resolution structural image was acquired using a T1-weighted, multiplanar reconstruction (MPR) sequence (TR = 1900 ms, TE = 3.42 ms, 192 slices, slice thickness = 1 mm, FOV = 256 mm, matrix size = 256×256).

Data preprocessing and statistical analyses were performed with Statistical Parametric Mapping (SPM12, Wellcome Department of Cognitive Neurology, London). The functional images were corrected for the delay in slice acquisition and were realigned to the first image to correct for interscan head movements. The individual T1-weighted, 3D structural image was co-registered to the mean EPI image generated after realignment. The co-registered structural image was then segmented into gray matter (GM), white matter (WM) and cerebrospinal fluid (CSF) using a unified segmentation algorithm (Ashburner and Friston, 2005). The functional images after slice timing and realignment procedures were spatially normalized to the Montreal Neurological Institute (MNI) space (resampled to $2 * 2 * 2$ mm^3) using the normalization parameters estimated during unified segmentation and then spatially smoothed with a Gaussian kernel of 6 mm full-width half-maximum (FWHM).

Data analyses

Behavioral data analyses

The proportion of loss trials and the average number of boxes opened in the Gain condition for each participant can be regarded as a measure of a participant's risk-taking tendency (Lejuez et al., 2002). The proportion of loss trials refers to the trial number of the Loss condition divided by the total number of trials. The average number of opening boxes in the Gain condition refers to the total number of collected gold coins divided by the trial number of the Gain condition. To investigate the difference of risk-taking tendency between two groups, independent sample t-tests were conducted.

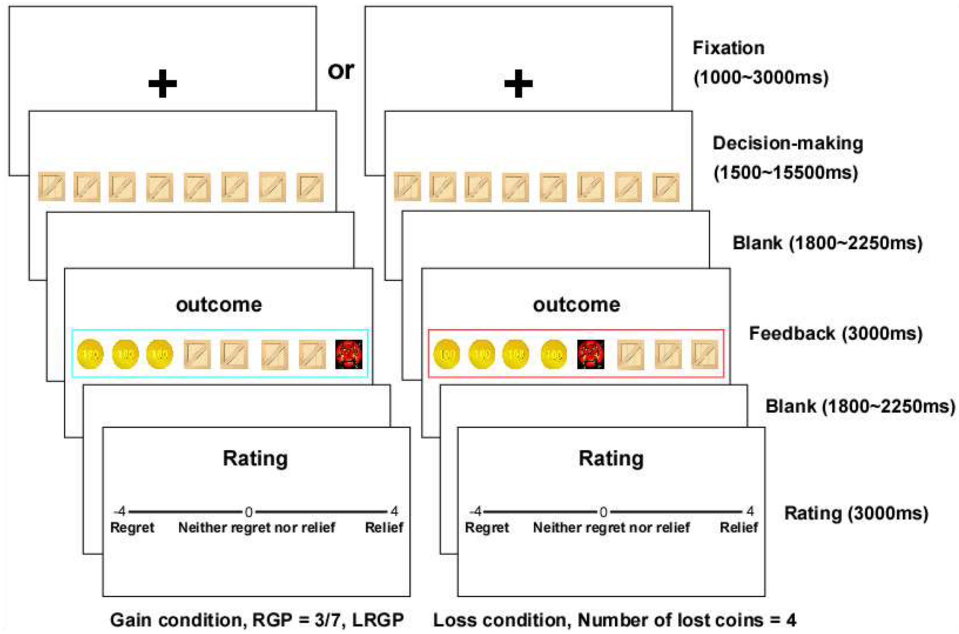

Fig. 1. Two possible conditions are displayed when participants play the task undergoing fMRI scanning. The left part of graph is Gain condition, in which participant collected three gold coins and missed four gold coins (the value of RGP is 3/7, belonged to LRGP). The right part of graph is Loss condition, in which participant lost four gold coins (the number of lost coins is 4). At the emotional rating stage, participants were asked to rate how they felt for their choice on a 9-point scale from extreme regret (defined as − 4) to extreme relief (defined as 4).

We calculated a combined index, called real gain percentage (RGP), which was defined as the ratio of the collected gain and the largest possible gain (that is, the total number of boxes before the devil) in a given trial (Liu *et al.*, 2016). The value of the RGP can be considered an indication of how good the outcome is on a particular trial. The Gain conditions were then divided into three levels according to the value of the RGP: (i) Low RGP (LRGP, poor outcome): $0 < RGP \leq 0.6$, (ii) Middle RGP (MRGP, moderate outcome): $0.6 < RGP \leq 0.8$ and (iii) High RGP (HRGP, optimal outcome): $0.8 < RGP \leq 1$. The division points between conditions were set post hoc to make trial numbers in each condition as similar to each other as possible (Liu *et al.*, 2018a).

In the Gain condition, in order to investigate the difference of participant's emotional sensitivity to objective outcome between two groups, regression analyses were performed within each participant. RGP level was defined as predictor and emotional rating as dependent variable. The regression coefficient (β_G) and intercept (β_{G0}) of each participant were calculated. β_G was considered as an index of participant's emotional sensitivity to objective outcome in Gain condition (Liu *et al.*, 2018b).

In the Loss condition, another regression analysis was performed within each participant, mirroring the previous analysis. The number of lost coins was defined as the predictor variable and emotional rating as the dependent variable. The regression coefficient (β_L) and intercept (β_{L0}) of each participant were calculated. β_L was considered as an index of participant's emotional sensitivity to objective outcome in Loss condition.

Previous research showed that emotional rating in a current trial could predict behavioral changes in the next trial. Such result was only found in the Gain_Gain condition (trials in which participants did not unpack the devil in both the current and the next trials) (Büchel *et al.*, 2011; Liu *et al.*, 2016). In the current study, to investigate the behavioral change between the current trial and the next, we restricted behavioral change analyses to the Gain_Gain condition. The behavioral change between the current trial and the next was defined as the difference in numbers of boxes being opened between two successive trials (Dif) (Liu *et al.*, 2016):

$$\text{Dif} = \text{Opened Boxes}_{t+1} - \text{Opened Boxes}_t$$

In the Gain_Gain condition, regression analyses within each participant were performed to replicate our previous finding that emotional rating in the current trial influenced behavioral change in the next trial (Dif). Emotional rating was defined as the independent variable, and inter-trial behavioral change (Dif) was defined as the dependent variable. The regression coefficient and intercept of each participant were calculated.

fMRI data analyses

First, a parametric analysis assessed how brain activity was modulated by objective outcome in both Tai Chi and control groups. The RGP level in the Gain condition and the number of lost coins in the Loss condition were used as parametric regressors, respectively. Furthermore, to investigate the relationship between brain regions and subjective emotional rating, an additional parametric analysis was performed in both Tai Chi and control groups. Here, the emotional ratings in Gain and Loss conditions were used as parametric regressors. Finally, a parametric analysis was performed to assess how brain activity in the t trial predicted the behavioral change in the t + 1 trial in the Gain_Gain condition. The Dif was used as the parametric regressor. For all parametric analyses, the conditions were time-locked to the presentation of the outcome of the final decision, convolved with a canonical hemodynamic response function (HRF). Additional covariates of no interest were created for movement-related variance and the decision-making phase.

High-pass temporal filtering with a cutoff of 128 s was also applied in the models. The resulting subject-specific estimates of the parametric regressors at each voxel were then entered into a second-level one sample *t*-test.

Then, to explore common brain regions between the two groups, a conjunction analysis using the conjunction null hypothesis was conducted (Nichols *et al.*, 2005). To investigate the different neuronal regions between Tai Chi and control groups, two groups were masked by each other at a threshold of $P < 0.01$ (note that a more liberal threshold of the exclusive mask reflects a more conservative approach (Uncapher and Rugg, 2009).

To further verify the conjunction and exclusion analyses in Gain condition, the general linear model (GLM) was conducted in SPM12. At the first level analyses, four types of outcomes were defined in Tai Chi or control group: LRGP outcome (Tai Chi: $M = 18.7$ trials, s.d. = 6.23; Control: $M = 10.8$ trials, s.d. = 6.47), MRGP outcome (Tai Chi: $M = 14.7$ trials, s.d. = 4.16; Control: $M = 12.0$ trials, s.d. = 4.72), HRGP outcome (Tai Chi: $M = 13.4$ trials, s.d. = 3.36; Control: $M = 15.9$ trials, s.d. = 3.19) and loss outcome (Tai Chi: $M = 33.2$ trials, s.d. = 4.17; Control: $M = 41.2$ trials, s.d. = 7.98). All of outcomes were time-locked to the presentation of the outcome of final decision with a duration of 3 s, convolved with a canonical hemodynamic response function (HRF). Additional covariates of no interest were created for decision-making phase (also convolved with hemodynamic response function (HRF)) and movement-related variance. High pass temporal filtering with a cutoff of 128 s was applied in the model. The four first level contrast images from each participant were analyzed at the second level. Then, bilateral ventral striatum (VS) identified in conjunction analysis and anterior cingulate cortex (ACC) identified in exclusion analysis were defined as regions of interest (ROIs). The ROIs were built as spheres with a diameter of 8 mm centered at MNI coordinates − 20/2/-6 (left VS), 14/6/-4 (right VS) and − 2/36/18 (left ACC) by using MarsBar toolbox in SPM12. Parameter estimates of signal intensity were extracted from these ROIs. To investigate the different change of ROI activations from LRGP outcome to HRGP outcome between Tai Chi and control groups, we conducted a 2 (Group: Tai Chi and Control) × 3 (Outcome: LRGP, MRGP and HRGP) repeated measures ANOVA based on parameter estimates of each ROI.

Additionally, to investigate how functional connectivity across brain regions associated with regret processing varied along different RGP levels, a psycho-physiological interaction (PPI) analysis (Friston *et al.*, 1997; O'Reilly *et al.*, 2012) was carried out in both Tai Chi and control groups. We first used left VS (MNI − 20 2–6), identified in the parametric analysis (i.e. left VS showed increased activation from LRGP to HRGP), to serve as the individual seed voxels. For each participant, we searched within an 8 mm (diameter) sphere around the coordinates of left VS from the second-level analysis to determine their individual peak voxels. The time series which were extracted from an 8 mm-diameter-sphere drawn around the individual activation peaks served as the physiological variable. The PPI analysis was then carried out (psychological variable: 1 for HRGP condition, −1 for LRGP condition) for each participant and a design matrix was created with the interaction term, the psychological variable and the physiological variable as regressors. Participant-specific contrast images of the interaction term entered into a second-level random-effects analysis using a one-sample t test.

For all analyses, BDI-II scores and BIS-11 scores were included as covariates of no interest at the second level of fMRI analyses. Moreover, a peak-level threshold of $P < 0.05$ (FWE) was used to define activations and all of the clusters survived at this threshold were reported.

Finally, to investigate the relationship among participant's emotional sensitivity to outcome, the score of questionnaires and brain data, we ran mediation analyses in both Tai Chi and control groups respectively.

Results

Demographic data and scale data

There were no significant difference in age ($t_{(60)} = 1.255$, $P = 0.214$), education ($t_{(60)} = 0.939$, $P = 0.351$) and time spent on physical exercise per day ($t_{(60)} = 1.010$, $P = 0.317$) (Table 1, Table S1 showed the range of each index). The Tai Chi group scored lower on neuroticism ($t_{(60)} = -2.024$, $P < 0.05$), while scoring higher on nonjudging ($t_{(50)} = 2.127$, $P < 0.05$), nonreactivity ($t_{(50)} = 3.047$, $P < 0.01$), total score of FFMQ ($t_{(50)} = 2.204$, $P < 0.05$) and MAAS ($t_{(50)} = 2.150$, $P < 0.05$) relative to the control group. No other significant difference was found between the two groups (Table 2, Table S2 showed the range of each index).

Behavioral results for risk-taking tendency

The results revealed that both the proportion of loss trials ($t_{(60)} = 3.78$, $P < 0.01$) and the average number of boxes opened ($t_{(60)} = 4.212$, $P < 0.01$) in the Tai Chi group were significantly lower than the control group. Moreover, the total number of gained coins from the task showed no significant difference between the two groups ($t_{(60)} = 0.600$, $P > 0.05$) (Table 3).

Behavioral results for subjective emotional rating

In Gain condition, the results showed β_G in two groups were significantly larger than zero (*ts* < 15.043, *ps* < 0.01). The results revealed that participants experienced less regret (more relief) from poor to optimal outcome. Moreover, independent samples *t*-tests showed β_G ($t_{(60)} = 8.74$, $P < 0.01$) and β_{G0} ($t_{(60)} = 8.99$, $P < 0.01$) in the Tai Chi group were significantly smaller than that in control group (Table 4). In addition, correlation analyses showed that nonjudgment of inner experience was negatively correlated with β_G in the Tai Chi group ($r = -0.487$, $P < 0.05$, Figure 2A). No significant correlation between nonreactivity and β_G was found ($r = 0.122$, $P > 0.05$). Moreover, a 2 (Group: Tai Chi

Table 1. Demographics of both groups

	Tai Chi group	Control group	*t*	*P*
Age (years)	64.94 ± 2.37	64.06 ± 3.05	1.255	0.214
Gender (male/female)	10/21	10/21	NA	NA
Education (years)	10.52 ± 1.91	11.03 ± 2.39	0.939	0.351
Tai Chi practice (years)	9.98 ± 5.16	0	NA	NA
Physical exercise time per day (minutes)	66.36 ± 21.96 (Tai Chi exercise)	60.14 ± 27.16 (Other exercise)	1.010	0.317

Table 2. Scale data of both groups

Psychological measures		Tai Chi group	Control group	t	P
BDI-II					
	Depressive	5.00 ± 5.25	5.87 ± 5.16	−0.658	0.513
BIS-11					
	Motor impulsive	22.58 ± 12.71	28.71 ± 13.12	−1.869	0.067
	Cognitive impulsive	71.94 ± 10.93	70.56 ± 14.74	0.416	0.679
	Nonplanning impulsive	76.13 ± 16.97	69.44 ± 19.88	1.426	0.159
	Total score of BIS-11	56.88 ± 6.63	56.24 ± 10.85	0.283	0.779
NEO-FFI					
	Neuroticism	27.32 ± 7.75	30.97 ± 6.36	−2.024	0.047*
	Extraversion	42.58 ± 6.38	41.61 ± 5.39	0.645	0.521
	Openness	39.48 ± 5.24	39.65 ± 4.76	−0.127	0.900
	Agreeableness	45.00 ± 6.29	43.94 ± 5.26	0.723	0.473
	Conscientiousness	48.55 ± 6.08	48.61 ± 5.04	−0.046	0.964
FFMQ					
	Observe	3.50 ± 0.79	3.21 ± 0.62	1.448	0.154
	Describe	3.55 ± 0.66	3.50 ± 0.50	0.328	0.744
	Act with awareness	3.19 ± 0.62	3.78 ± 0.70	−0.415	0.680
	Nonjudge	2.86 ± 0.49	2.56 ± 0.45	2.277	0.027*
	Nonreact	3.58 ± 0.46	3.13 ± 0.59	3.018	0.004**
	Total score of FFMQ	17.16 ± 1.83	16.18 ± 1.51	2.114	0.039*
MAAS					
	Total score of MAAS	72.54 ± 11.72	64.62 ± 14.75	2.144	0.037*

The sequential Bonferroni correction was used to correct the P value in the correlation analyses.
*$P < 0.05$, **$P < 0.01$

Table 3. Risk-taking tendency of both groups

	Tai Chi group	Control group	t	P
The proportion of loss trials	42.7% ± 7.7%	51.3% ± 10.1%	3.780	0.000**
The average number of opened boxes in gain trials	3.65 ± 0.58	4.26 ± 0.56	4.212	0.000**
The total number of gained coins in the task	164.32 ± 16.28	161.65 ± 18.96	0.600	0.550

*$P < 0.05$, **$P < 0.01$

Table 4. Regression analyses of both groups

Condition	Value	Tai Chi group	Control group	t	P
Gain					
	β_G	1.29 ± 0.69	2.02 ± 0.75	3.962	0.000**
	β_{G0}	−0.81 ± 1.70	−2.39 ± 2.27	3.114	0.003**
Loss					
	β_L	−0.27 ± 0.38	−0.43 ± 0.30	1.868	0.067
	β_{L0}	−0.22 ± 0.82	−0.61 ± 1.10	1.584	0.119

Note. *$P < 0.05$, **$P < 0.01$

and control) * 3 (Outcome: LRGP, MRGP, and HRGP) repeated measures ANOVA on emotional rating was also conducted (Figure 2B). The main effect of Outcome ($F_{(2,118)} = 203.11$, $P < 0.01$) reflected higher emotion rating as outcome improved. A significant interaction between Group and Outcome was detected ($F_{(2,118)} = 11.45$, $P < 0.01$). The follow-up *t*-tests showed that emotional rating for poor outcome was higher in Tai Chi group than in control group ($t_{(60)} = 2.772$, $P < 0.01$) and emotional rating for optimal outcome was lower in Tai Chi group than in control group ($t_{(60)} = 2.621$, $P < 0.05$). No significant difference of emotional rating for moderate outcome was found between two groups ($t_{(60)} = 0.218$, $P > 0.05$) and there was no significant main effect of group ($F_{(2,118)} = 11.45$, $P > 0.05$).

In Loss condition, the relationship between emotional rating and lost coins for two groups is reflected in Figure 2C. The β_L in the two groups were significantly smaller than zero ($ts < -8.047$, $ps < 0.01$). Participants experienced less regret with a decreasing number of lost coins. Independent sample *t*-tests showed β_L in Tai Chi group had a tendency to be smaller relative to the control group, although this did not reach statistical significance ($t_{(60)} = 1.868$, $P = 0.067$) (Table 4). β_{L0} showed no significant difference between the two groups ($t_{(60)} = 1.584$, $P > 0.05$).

Behavioral results about the prediction of emotional rating on subsequent behavioral change

In the Gain_Gain condition, the regression coefficients in two groups were significantly smaller than zero ($ts < -7.544$, $ps < 0.05$), indicating that if participants experienced regret due to risk aversion at t trial, they tended to take more risk at t + 1 trial. In addition, regression coefficient ($t_{(60)} = 0.267$, $P > 0.05$) and intercept ($t_{(60)} = 1.301$, $P > 0.05$) did not show a significant difference between the two groups.

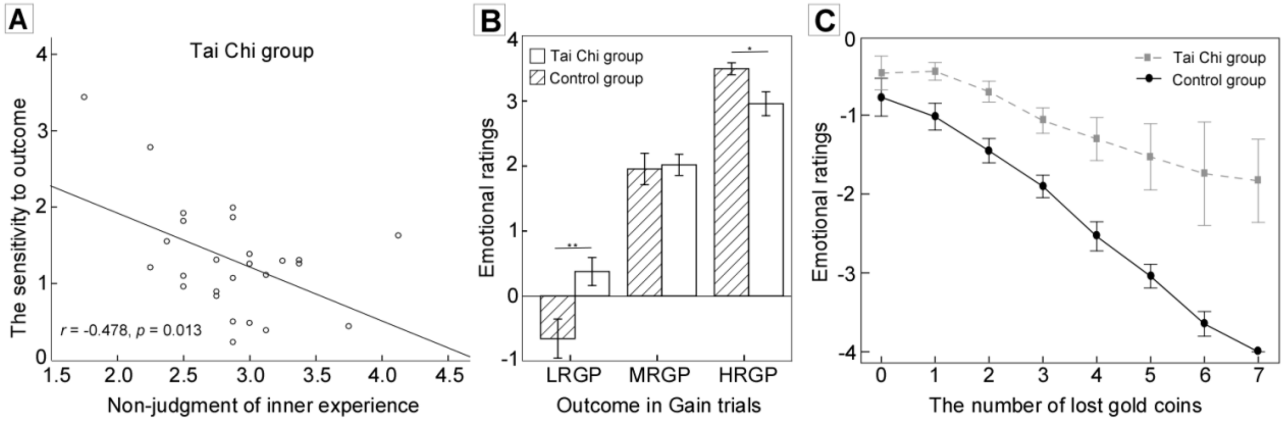

Fig. 2. (A) The negative correlation between nonjudging of inner experience and β_G (an index of participant's sensitivity to objective outcome) was found in Tai Chi group ($r = -0.487$, $P < 0.05$). (B) In Gain condition, the 2 (Group: Tai Chi and control) * 3 (Outcome: LRGP, MRGP, and HRGP) repeated measures ANOVA on emotional rating showed significant main effect of Outcome ($F_{(2,118)} = 203.11$, $P < 0.01$) and significant interaction between Group and Outcome ($F_{(2,118)} = 11.45$, $P < 0.01$). Furthermore, Tai Chi group showed higher emotional rating for LRGP outcome ($t_{(60)} = 2.772$, $P < 0.01$) and lower emotional rating for HRGP outcome ($t_{(60)} = 2.621$, $P < 0.05$) than control group. In addition, no significant difference of emotional rating for MRGP outcome was found between two groups ($t_{(60)} = 0.218$, $P > 0.05$). Error bars indicated standard error. (C) In Loss condition, the relationship between emotional rating and lost coins was described for two groups. Error bars indicated standard error.

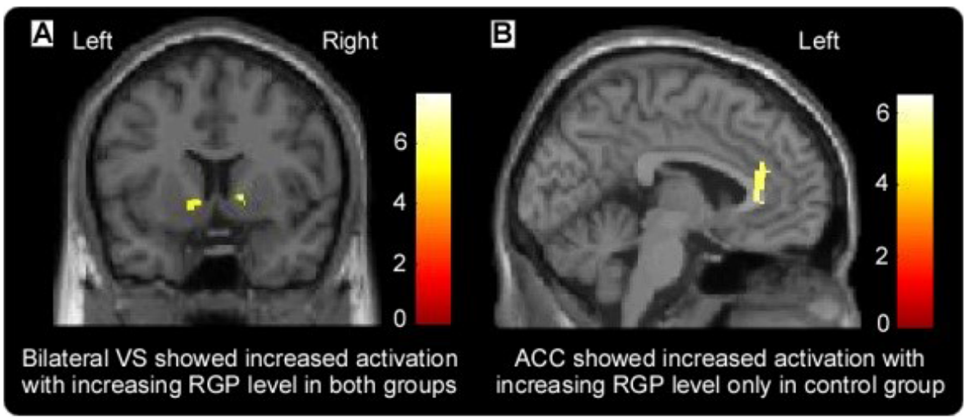

Fig. 3. (A) Common brain regions between two groups in Gain condition. Bilateral ventral striatum showed increased activation with increasing RGP level in both Tai Chi and control groups. (B) ACC showed increased activation with increasing RGP level only in control group.

fMRI results in Gain condition

Parametric analyses. In the Gain condition, parametric analyses were conducted to explore the relationship between brain regions and RGP level or emotional rating. The results of these parametric analyses for each group are shown in Supplementary Material (Supplementary Table S3 and S4).

The results revealed that bilateral VS were activated in both Tai Chi and control groups with outcome getting better (Figure 3A and Table 5). A 2 (Group: Tai Chi and Control) * 3 (Outcome: LRGP, MRGP and HRGP) repeated measures ANOVA on the activations of bilateral VS revealed significant main effects of Outcome (Left VS: $F_{(2,102)} = 23.43$, $P < 0.01$; Right VS: $F_{(2,102)} = 23.36$, $P < 0.01$), indicating increased bilateral VS activation from LRGP to HRGP. No significant main effects of Group (Left VS: $F_{(1,51)} = 0.50$, $P > 0.05$; Right VS: $F_{(1,51)} = 0.02$, $P > 0.05$) and Group * Outcome interaction were found (Left VS: $F_{(2,102)} = 1.66$, $P > 0.05$; Right VS: $F_{(2,102)} = 1.54$, $P > 0.05$).

Moreover, the results found that the ACC showed increased activation with outcome getting better only in control group (Figure 3B, Table 6). A 2 (Group: Tai Chi and Control) * 3 (Outcome: LRGP, MRGP and HRGP) repeated measures ANOVA on the activation of ACC revealed significant main effects of Outcome ($F_{(2,102)} = 16.73$, $P < 0.01$), indicating increased ACC activation from LRGP to HRGP. The Group * Outcome interaction was also significant ($F_{(2,102)} = 4.04$, $P < 0.05$). Further analysis revealed that control group showed stronger deactivation relative to Tai Chi group in LRGP, no significant difference was found in MRGP and HRGP. No significant main effects of Group was found ($F_{(1,51)} = 1.69$, $P > 0.05$). Bilateral cerebellum and right PCC showed increased activation with outcome getting better only in Tai Chi group (Supplementary Table S5).

In addition, VS showed increased activation with increasing emotional rating in both groups (Table 5). No specific region showed increased activation with increasing emotional rating in the Tai Chi or control groups.

PPI analyses. In the Tai Chi group, left VS showed significantly higher functional connectivity with bilateral middle frontal gyrus (MFG), right superior frontal gyrus (SFG) and bilateral inferior frontal gyrus (IFG) for poor outcome as compared to optimal outcome (Figure 4, Table 7). No such significant effect was found in the control group.

Table 5. Common regions between two groups in Gain condition

Region		Peak activation X	Y	Z	t Value	Voxels
Increased with increasing RGP level						
L	Precuneus	−16	−50	66	6.79	1194
R	Linual gyrus	12	−68	−6	7.64	1099
L	Supramarginal gyrus	−2	−20	40	5.97	277
L	Calcarine gyrus	−6	−98	6	6.77	234
R	Superior occipital gyrus	18	−86	20	5.47	60
L	Ventral striatum	−20	2	−6	5.97	54
R	Ventral striatum	14	6	−4	5.49	32
Increased with decreasing RGP level						
No region						
Increased with increasing emotional rating						
L	Precuneus	−36	−24	68	7.97	1351
R	Cerebelum	16	−48	−16	8.22	1200
L	Rolandic operculum	−42	−22	22	6.65	184
L	Ventral striatum	−28	−14	4	5.35	42
L	Middle occipital gyrus	−18	−94	6	5.44	41
Increased with decreasing emotional rating						
No region						

Coordinates (mm) are in MNI space. L = left hemisphere; R = right hemisphere. All the clusters survived FWE correction ($P < 0.05$) for multiple comparisons at the peak level.

Table 6. Specific regions for control group in Gain condition

Region		Peak activation X	Y	Z	t Value	Voxels
Increased with increasing RGP level						
L	Rolandic operculum	−40	−6	12	6.52	158
L	ACC	−2	36	18	5.39	151
L	ACC	0	40	6	5.27	
R	Middle temporal gyrus	56	−22	−14	5.91	36
R	ACC	8	52	16	5.28	6
Increased with decreasing RGP level						
No region						
Increased with increasing emotional rating						
L	Rolandic operculum	−42	−16	22	6.77	281
L	Middle temporal gyrus	−42	−50	8	5.87	30
Increased with decreasing emotional rating						
No region						

Coordinates (mm) are in MNI space. All the clusters survived FWE correction ($P < 0.05$) for multiple comparisons at the peak level.
Italic means the region is not the peak region in the cluster.

Correlation analyses. Changes in VS-SFG connectivity between poor and optimal outcome ($VS\text{-}SFG_{LRGP}$—$VS\text{-}SFG_{HRGP}$) was positively correlated with nonjudgment of inner experience in the Tai Chi group ($r = 0.469$, $P < 0.05$). Moreover, a negative correlation between VS-SFG connectivity change and emotional sensitivity to outcome (β_G) was also found in the Tai Chi group ($r = -0.490$, $P < 0.05$). There were no significant correlations between nonjudgment of inner experience and connectivity in the control group.

Mediation analyses. The results above indicated the relationship among participant's emotional sensitivity to outcome (β_G), nonjudgment of inner experience and VS-SFG connectivity change in the Tai Chi group. The further data-driven mediation analysis showed that there was no significant effect of VS-SFG connectivity change on participant's emotional sensitivity to outcome (β_G) after including nonjudgment of inner experience (Figure 5, path a: $\beta = 0.469$, $P < 0.05$; path b: $\beta = -0.645$, $P < 0.01$; path c: $\beta = -0.490$, $P < 0.05$; path c': $\beta = -0.240$, $P > 0.05$). Thus, nonjudgment of inner experience fully mediated the impact of VS-SFG connectivity change on participant's emotional sensitivity to outcome (β_G).

fMRI results in Loss condition

Parametric analyses. In the Loss condition, parametric analyses assessed how brain activity was modulated by objective outcome (lost coins) in both Tai Chi and control groups. The

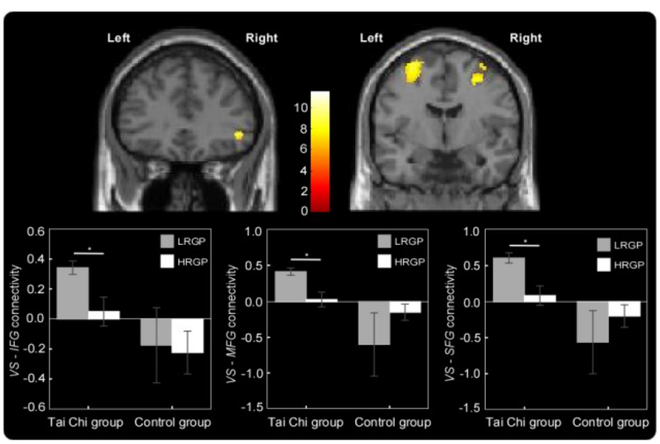

Fig. 4. In Tai Chi group, VS showed significantly higher functional connectivity with MFG, SFG and IFG in LRGP outcome as compared to HRGP outcome. No such significant effect was found in control group.

results from parametric analyses in each group are shown in Supplementary Material (Supplementary Table S6 and S7).

The results revealed that bilateral VS were activated in both Tai Chi and control groups with decreasing number of lost coins (Figure 6A and Supplementary Table S8). No region showed increased activations with increasing number of lost coins in both the Tai Chi and control groups. Moreover, the results showed insula was activated only in the Tai Chi group (Supplementary Table S9), whereas no region was activated specifically in the control group.

No regions showed increased activations with changing emotional rating in either the Tai Chi or control groups (Supplementary Table S6 and S7).

Correlation analyses. The parametric analysis in the Loss condition revealed increased activation of VS as the number of lost coins decreased. Beta values of the VS in the parametric analysis (β_{VS}) were extracted for each participant, to serve as an individual difference measure of VS sensitivity toward lost coins. β_{VS} was negatively correlated with risk-taking tendency (the average number of opening boxes in Gain) in control group ($r = -0.457$, $P < 0.05$) (Figure 6B).

fMRI results in Gain_Gain condition

Parametric analyses. In the Gain_Gain condition, a parametric analysis was performed to assess how brain activity in the t trial predicted behavioral change in the t + 1 trial in both Tai Chi and control groups. The results from parametric analyses of each group are shown in Supplementary Material (Supplementary Table S10).

Table 7. For Tai Chi group, brain regions showed stronger functional connectivity with VS in LRGP relative to HRGP

Region		Peak activation X	Y	Z	t Value	Voxels
R	Middle occipital gyrus	34	−72	28	11.52	11 005
L	*Inferior parietal lobule*	−28	−54	54	9.66	
L	Precentral gyrus	−40	2	42	8.82	866
R	Middle frontal gyrus	30	−2	54	8.53	311
R	*Superior frontal gyrus*	36	−4	66	7.19	
R	Inferior frontal gyrus	48	34	−4	7.74	101
R	Precentral gyrus	56	12	34	7.99	63
L	Inferior frontal gyrus	−46	24	−8	7.04	27
L	Middle frontal gyrus	−52	14	40	6.96	16

Coordinates (mm) are in MNI space. All the clusters survived FWE correction ($P < 0.05$) for multiple comparisons at the peak level.
Italic means the region is not the peak region in the cluster.

The results revealed that the ACC showed increased activation with decreasing Dif only in the control group (Table 8), whereas no region was activated specifically in the Tai Chi group.

Discussion

In the current cross-sectional study, we employed a modified sequential risk-taking task to investigate the effect of long-term Tai Chi practice on nonjudgment of inner experience and regret in older adults. Behaviorally, the Tai Chi group showed a higher propensity to adopt a nonjudgmental stance toward their inner

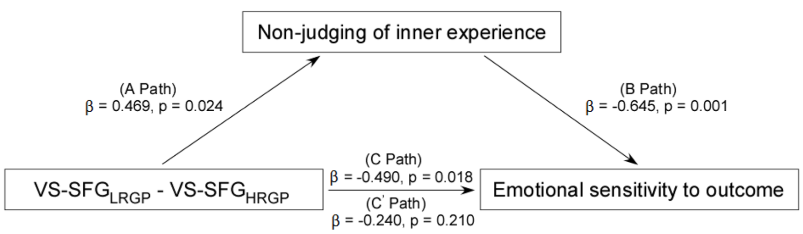

Fig. 5. The mediation analysis showed that there was no significant effect of VS-SFG connectivity change on participant's sensitivity to outcome (β_G) after including nonjudge of inner experience (path a: $\beta = 0.469$, $P < 0.05$; path b: $\beta = -0.645$, $P < 0.01$; path c: $\beta = -0.490$, $P < 0.05$; path c': $\beta = -0.240$, $P > 0.05$).

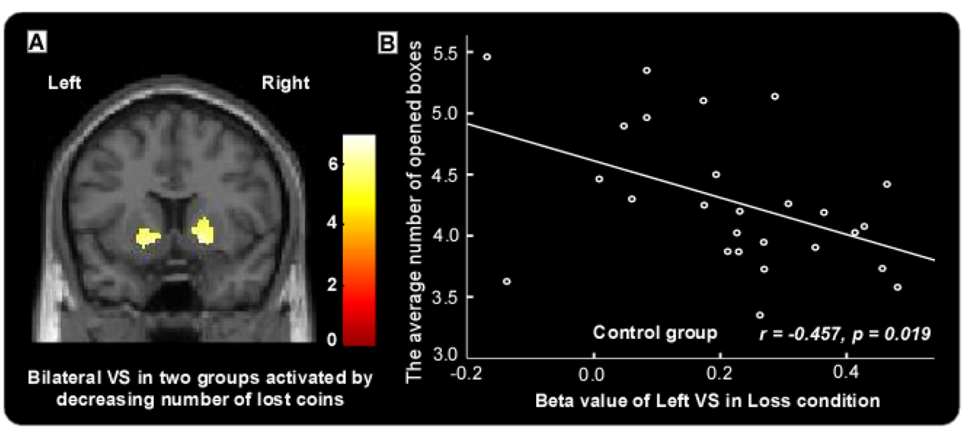

Fig. 6. (A) Common brain regions between two groups in Loss condition. Bilateral VS showed increased activation with decreasing number of lost coins in both Tai Chi and control groups. (B) The correlation analysis found β_{VS} was positively correlated with risk-taking tendency in control group ($r = 0.457$, $P < 0.05$).

Table 8. Specific regions for control group in the t trial could predict behavioral changes in the t + 1 trial

Region		Peak activation			t Value	Voxels
		X	Y	Z		
Increased with decreasing Dif						
L	ACC	−8	40	2	5.38	5
Increased with increasing Dif						
No region						

Coordinates (mm) are in MNI space. All the clusters survived FWE correction ($P < 0.05$) for multiple comparisons at the peak level.

experience, less risk-taking, less regret and less emotional sensitivity to outcome than the control group. Furthermore, we found that nonjudgment of inner experience protected against emotional reactivity to outcome (such as feelings of regret to missed chances) in the Tai Chi group. At the neural level, both groups showed increased VS activation as optimal outcome increased. For the Tai Chi group, functional connectivity of the VS with SFG, MFG and IFG changed as a function of outcome. Specifically, stronger connectivity was found in trials with a poor outcome (many missed chances) relative to trials when outcome was optimal (maximum amount of coins obtained). Nonjudgment of inner experience in the Tai Chi group fully mediated the impact of VS-SFG functional connectivity on participants' emotional sensitivity to outcome. In the control group, activation level of the ACC increased with optimal outcome. Interesting, activation in this ACC region also predicted reduced risk-taking tendency in the subsequent trial in the control group only. This thus implicates the ACC as a core region, reflecting emotional reactivity to a large gain which in turn diminishes subsequent risk taking behavior, a pattern not observed in the Tai Chi group.

In line with our hypothesis, we found that long-term Tai Chi exercise was associated with enhanced nonjudgment of inner experience and reduced feelings of regret. Previous studies have revealed that a practical method to reduce rumination is through the promotion of a strategy whereby inner experience is not judged, this has also been identified as a key component of meditation (Wang *et al.*, 2010; Wayne *et al.*, 2014). Accordingly, various studies have demonstrated that meditation training leads to reduced rumination in adults (Coffey *et al.*, 2010), with the degree of rumination also linked to a propensity to experience regret (Roese *et al.*, 2009). The thing to be noted is that the current study did not reveal the causality between Tai Chi exercise and reduced feelings of regret, i.e. Tai Chi exercise decreases the feelings of regret or older adults with less regret feelings like Tai Chi exercise. According to the notion that meditation training could reduce rumination mentioned above, we tend to infer that Tai Chi exercise might affect the feelings of regret.

In the Tai Chi group, a strong stance to not-judge inner experience might have mitigated the abstract self-evaluative thoughts characteristic of rumination, thereby reducing the intensity of counterfactual thinking, a core component of regret. We observed that the Tai Chi group was less sensitive to outcome than the control group. Specifically, Tai Chi training was associated with less regret for a poor outcome but also reduced excessive relief for an optimal outcome. Tai Chi training might decrease older adults' emotional sensitivity to outcome, as a reflection of stronger emotion regulation. This inference was supported by our another result that the nonjudgment of inner experience was negatively correlated with the emotional sensitivity to outcome in the Tai Chi group. Previous work has shown that meditation is an effective way to improve individuals' core psychological and cognitive ability, including emotional regulation (Tang *et al.*, 2015). In addition, trait meditation is associated with less use of maladaptive emotion regulation strategies (Hill and Updegraff, 2012) and reduced physiological emotional responding in the presence of stress (Arch and Craske, 2010). Taken together, our results suggest that long-term Tai Chi practice might be an effective way to improve emotion regulation for older adults through enhanced nonjudgment of inner experience.

The current study also indicated that long-term Tai Chi training may modulate older adults' behavior during the sequential risk-taking task. Specifically, the Tai Chi group took less risks than control group. It is worth noting that the total gain showed no significant difference between the two groups. Thus, compared with the control group, the Tai Chi group accomplished their tasks equally well with less risk-taking behavior. On the one hand, the elderly may be vulnerable to injury and falls that can produce serious injuries in this group. One reason that Tai Chi may produce fewer falls in the elderly is that they are being more careful and taking fewer risks. The elderly are also financially vulnerable and may benefit from less financial risk taking in protecting their available resources. On the other hand, risk taking is thought to decrease throughout adulthood. A common notion is that adolescence and young adulthood is a time of impulsiveness and risk seeking, whereas as one ages, one becomes more risk-aversive, with older adulthood being the pinnacle of cautious decision making and risk aversion Lee *et al.*, 2008). Thus, risk aversion might be representative of rational decision making in older adults. Previous work suggests that meditation could modulate individuals' decisions in a more rational way (Tang *et al.*, 2015). For instance, Kirk and colleagues (2011) found that compared with controls, experienced meditators were more rational and exhibited greater acceptance rates for highly asymmetric offers in an ultimatum game (Kirk *et al.*, 2011). Accordingly, for older adults, the meditation component in Tai Chi practice might play a vital role in the guidance of rational decision making.

For the Tai Chi group, VS showed significantly higher functional connectivity with frontal regions, such as SFG, MFG and IFG, in trials with LRGP as compared to HRGP. Moreover, changes in VS-SFG connectivity between poor and optimal outcomes were positively correlated with nonjudgment of inner experience. Meditation has been shown to modulate the functional connectivity between frontal regions (Brewer *et al.*, 2011). For example, Brewer and colleagues (2011) found increased functional connectivity between the PCC, dorsal ACC and dorsolateral PFC in experienced meditators, interpreted as indicating increased cognitive control over the function of the default mode network (DMN). Increased functional connectivity was also found between DMN regions and the ventromedial PFC in participants with more compared with less meditation experience (Hasenkamp and Barsalou, 2012). To our knowledge, this study is the first to report that VS-frontal functional connectivity maybe be modulated by meditation experience. This finding might be related to the specific task employed, which emphasized reflexive control of emotions. The current study also revealed that nonjudgment of inner experience in the Tai Chi group fully mediated the impact of VS-SFG functional connectivity on participants' emotional sensitivity to outcome. However, our previous resting-state fMRI study found that Tai Chi practitioners' resting-state functional connectivity within the executive control network mediated the effect of meditation on their emotion regulation (Liu *et al.*, 2018b). The inconsistent results might be due to the sequential risk taking task the current study used, i.e. the brain activity pattern of Tai Chi practitioners in the face of poor outcome was different from that in the resting state.

For the control group, activation of the VS to loss was inversely related to risk-taking tendency cross participants; the more sensitivity a participant's striatum was toward lost coins, the less risk he/she would take. Less risk-taking might represent stronger loss aversion for a participant. It is well established that the VS plays a central role in adjusting behaviors in order to maximize rewarding or minimize aversive outcomes (Daniel and Pollmann, 2014). In the present study, VS response to lost coins showed no significant difference between two groups, but striatum sensitivity to loss predicted loss aversion behavior only for the control group. Meditation incorporates the process of attending to present moment sensations and experienced with a nonjudgmental stance. Our results indicate that meditation, a key component of long-term Tai Chi training, might have disrupted the association between initial response to loss and successive loss aversion.

Engagement of the ACC occurred in controls as outcome was increasingly optimized, potentially reflecting changes in visceral arousal (Critchley *et al.*, 2005) associated with greater emotional experience to positive outcomes in this group. This in turn may have lessened future risk taking behavior, as ACC activation predicted reduced subsequent risk taking in the control group (i.e. the stronger activation of ACC in t trial, the less risk taking in $t+1$ trial). The role of the ACC in top-down cognitive control has been frequently demonstrated in previous studies (Rogers *et al.*, 2004; Chudasama *et al.*, 2013). Interestingly, the Tai Chi group took less risk than the control group without the activation of ACC being found. Such a result might suggest that, unlike controls who need the involvement of prefrontal regions to guide behaviors in a top-down manner, long-term Tai Chi practitioners might control risk taking behaviors in a more automatic manner. These findings are in line with previously revealed differences between novice and expert meditators. Specifically, the process of meditation has been characterized as an active cognitive regulation in novice meditators, who needed to overcome habitual ways of internally reacting to their own emotion, potentially reflected in greater prefrontal activation. However, expert meditators might not use this prefrontal control. Rather, they may have automated an accepting stance toward their experience and thus no longer engage in top-down control efforts but instead show enhanced bottom-up processing (Chiesa *et al.*, 2013).

In conclusion, by using the sequential risk-taking task, the present fMRI study found, for older adults, long-term Tai Chi practice could improve nonjudgment of inner experience, automatically lessen feelings of regret, reduce emotional sensitivity to outcome and guide behavior in a rational way. On the neural level, although both groups showed increased VS to better outcome and increasing emotional rating in the Gain condition or with decreasing amount of loss in Loss condition, some notable differences between two the groups were revealed. Specifically, only in the control group did we found that activation of ACC increased as subjective outcome got better in Gain condition, and that activation of ACC predicted reduced subsequent risk-taking behavior. Moreover, a positive cross-participant correlation was found between loss-related activation of VS and an individual's risk-taking tendency, but only for the control group. On the other hand, only in the Tai Chi group, was stronger VS-frontal functional connectivity observed in trials with poor outcome as compared to optimal outcome. Additionally, in the Tai Chi group, the nonjudgment of inner experience fully mediated the impact of VS-SFG functional connectivity on participants' emotional sensitivity to outcome. Together, the current study showed that long-term Tai Chi practice might be an effective way for older adults to improve nonjudgment of inner experience and emotion regulation by strengthening VS-frontal functional connectivity.

Limitations

The current study has some limitations that should be addressed. First, participants in the control group should perform the same physical activities. However, matching participants on this variable proved to be difficult. Second, the current study was a cross-sectional study. Therefore, the relationship between reduced feelings of regret and Tai Chi practice should be carefully considered when attributing causality. In our future work, we plan to perform a longitudinal study to clearly explore the casual relationship between regret and Tai Chi practice.

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Supplementary data

Supplementary data are available at *SCAN* online.

Conflict of interest

None declared.

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