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ORIGINAL RESEARCH

“Practice makes perfect?” white matter microstructural characteristic predicts the degree of improvement in within-trial conflict processing across two weeks

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Abstract

Several studies have investigated the trait-like characteristics of conflict processing at different levels. Our study extends these findings by reporting a practice-based improvement in within-trial conflict processing across two sessions. Eighty-three participants performed the same flanker task on two occasions 2 weeks apart. A subset of 37 subjects also underwent diffusion tensor imaging (DTI) scanning the day before the first behavioral task. Despite the trait-like characteristics of conflict processing, within-trial conflict processing in the second behavioral session was significantly shorter than that in the first session, indicating a practice-based improvement in conflict processing. Furthermore, changes in within-trial conflict processing across the two sessions exhibited significant individual differences. Tract-based spatial statistics revealed that the improvement across two sessions was related to the axial diffusivity values in white matter regions, including the body and splenium of the corpus callosum, right superior and posterior corona radiate, and right superior longitudinal fasciculus. Subsequently, lasso regression with leave-one-out cross validation was used to assess the predictive ability of white matter microstructural characteristics in significant regions. The results showed that 61% of individual variability in the improvement in the within-trial conflict processing could be explained by variations in the axial diffusivity values in the four significant regions and the within-trial conflict processing in the first session. These results suggest that axonal morphology in the white tracts connecting conflict-related regions predicts the degree of within-trial conflict processing improvement across two sessions.

Keywords Conflict processing · Trait · Individual differences · White matter microstructural characteristics · Regression analyses

Introduction

Conflict processing refers to the important human ability to adjust behavior appropriately according to the environment and goal demands (Cavanagh and Frank 2014; Cohen 2014). Experimental conflict paradigms produce a robust conflict effect, whereby reaction times (RTs) are longer in incongruent than congruent trials. It is suggested that the conflict effect reflects imperfect cognitive control when irrelevant stimuli distract the participants from responding. This control process is considered to be adaptive, which means that after experiencing a conflict situation, the system is better prepared for the next instance of conflict (Gratton et al. 1992). According to the conflict monitoring theory (Botvinick 2001), the medial frontal cortex (MFC) operates in a hub-like manner, monitoring ongoing conflict and enhancing functional communication with task-related regions such as the dorsolateral prefrontal cortex (DLPFC), which then perform cognitive control (Cohen 2014). A previous study found that the degree of activity in the lateral prefrontal cortex could be predicted by the activity in the MFC in the previous trial (Ridderinkhof et al. 2004). It has been suggested that conflict could be resolved at different levels (i.e., the within-trial and

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trial-by-trial levels) (Boy et al. 2010), which might activate different cells in the DLPFC (Mansouri et al. 2007)

Several studies have examined the test–retest reliability of conflict processing, using both behavioral and electrophysiological indices (Clayson and Larson 2013; Feldman and Freitas 2016). Despite the robust trait-like characteristics of conflict processing, it is interesting that RTs under all conditions were significantly shorter in the second session than in the first session, even when the sessions were 2 weeks apart. Differences in reaction times across two sessions may suggest practice-based improvement, reflecting the saying "practice makes perfect". In this study, using the Eriksen flanker task (Eriksen and Eriksen 1974), we aimed to extend these findings by investigating whether conflict processing abilities at different levels can be improved across two separate sessions.

Recently, the machine learning method has been widely used in clinical practice. Compared with traditional imaging studies that explore the underlying mechanisms, the machine learning method focuses on classification and prediction to propose personalized diagnosis and treatment strategies. For example, Redlich et al. (2016) used the machine learning method to predict the responses of patients with severe depression to electroconvulsive therapy. In some personnel selection cases, institutions want to be able to identify people who can make greater progress through several practice sessions, which is one purpose of the present study. It was recently proposed that white matter structures that control the speed of impulse conduction between distant regions are critical for learning (Fields 2008). More specifically, consistent evidence suggests that the white matter tracts connecting task-related regions are related to the learning potential in various domains (Floel et al. 2009; Meinzer et al. 2010; Wong et al. 2011). For example, the microstructural characteristics of the white matter tracts connecting the brain regions associated with auditory language processing can be used to predict individual differences in responsiveness to training in sound-to-word learning paradigms (Wong et al. 2011). In flanker tasks, conflict processing is largely dependent on the visuospatial attention system, which initiates and adjusts top-down visuospatial control to resolve conflict (Petersen and Posner 2012). In contrast to the fronto-parietal control system, which plays an important role in representing and maintaining context information (MacDonald et al. 2000), the visuospatial attention system, especially in the right hemisphere, participates in conflict processing by controlling the voluntary orientation of attention toward a target location (Gratton et al. 1992; Corbetta et al. 2000). Thus, it seems reasonable to speculate that the microstructural characteristics of the white matter backbones of the visuospatial attention system, such as the superior longitudinal fasciculus (SLF), will be related to improvements in conflict processing across two sessions.

Diffusion tensor imaging (DTI) is a non-invasive method that provides quantitative measures of white matter microstructure characteristics. These include axial diffusivity (AD), the degree of diffusion along the axon, which represents axonal morphology features such as the axon density and diameter (Song et al. 2003); radial diffusivity (RD), the degree of diffusion perpendicular to the axial direction, which reflects the degree of myelination (Tang et al. 2012); Fractional anisotropy (FA), the degree of anisotropy in the diffusion process; and mean diffusivity (MD), which measures the bulk diffusion without directional preferences. Using DTI, in this study we aimed to demonstrate that white matter tracts connecting the conflict-related networks are associated with subject-specific improvements in conflict processing across two sessions.

Thus, the current study had two major aims. First, we aimed to examine whether, at the group level, conflict processing abilities can be improved through practice across two sessions. Second, based on brain structure imaging, we aimed to build a model that can be used to identify people who can make greater progress through two practice sessions.

Material and methods

Participants

Eighty-three participants (all right-handed, 39 males) with an age range of 18–27 years (mean: 23, SD: 1.84) were recruited from Xidian University in China through a bulletin board. According to the schedules of the experiment and participants, a subset of 37 participants (all right-handed; 18 males; age, mean: 22 years, SD: 1.54, range: 18–26 years) underwent diffusion tensor imaging (DTI) scanning. There was no difference in demographics between two samples. All participants underwent a physical examination and questionnaires to exclude those with current or chronic physical illness, addiction (including excessive use of alcohol, nicotine, drugs, and caffeine users), neurological or psychiatric diseases, or a family history of neurological and psychiatric diseases. All participants had normal or corrected-to-normal vision and were experienced in using computer keyboard.

Procedure and task

Participants underwent two behavioral sessions two weeks apart. DTI data of 37 participants were collected the day before behavioral testing in the first session (Fig. 1). All participants were asked to continue with their usual sleep-wake cycles, and to avoid caffeine, alcohol, and strenuous exercise during the interval between two sessions.

For each session, participants completed a modified temporal flanker paradigm similar to the work of Duthoo et al. (2014). An array of five Arabic numerals was displayed in the center of the screen, consisting of a target digit with two

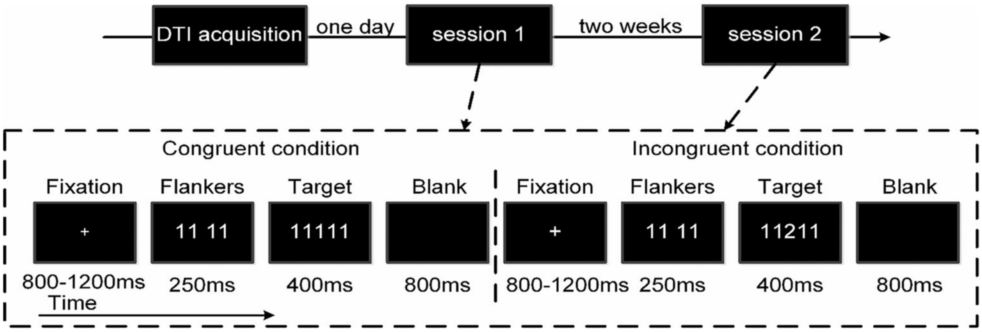

Fig. 1 Study design; for each trial, flanker digits could be congruent or incongruent with the target digit

flanker digits on both sides (1, 2, 3 or 4). The flanker digits were either the same as or different from the target digit, giving congruent (e.g., 111,111) or incongruent (e.g., 11,211) trials. Participants responded to the central digit by pressing the corresponding key on the keyboard (keys 1 and 2 were pressed with the left middle and index finger, and keys 3 and 4 were pressed with the right index and middle finger) and ignored the bilateral flanker digits. Participants were instructed to respond as quickly and accurately as possible.

Participants were required to complete four blocks, preceded by a short instruction slide and practice part with 20 trials. The practice part continued until all trials were successfully completed. For each of the four blocks, 49 trials were presented randomly: the first trial in each block was congruent (C) and was excluded from analysis. Of the remaining 48 trials, half were congruent (C) and the rest were incongruent (I). Some authors argue that CSE does not measure conflict adaptation but is instead biased by contingency learning and feature integration confounds (Mayr et al. 2003; Schmidt and De Houwer 2011). Thus, each of the four possible sequences, congruent followed by incongruent (CI), incongruent followed by incongruent (II), incongruent followed by congruent (IC) and congruent followed by congruent (CC), made up one-quarter of the total trials each to avoid the contingency learning confound. To avoid the feature integration confound, both flanker and target digits changed across two consecutive trials. Previous studies showed that conflict effect was modulated by the stimulus onset asynchrony (SOA) between targets and flankers. The asynchrony between the onsets of flanker and target digits yields an increased conflict effect compared to stimultaneous onset of flanker and target (Wendt et al. 2014). This is also interpreted by some authors as an important determinant of CSE (Weissman et al. 2015). Moreover, the present study is part of the entire researches of our team on conflict processing. Without prejudice to the purpose of the present study, we chose the asynchrony between the onset of flanker and target digits to ensure comparability between studies. In all trials, flanker digits preceded the target digit by 250 ms, then both remained on the screen for 400 ms followed by an 800-ms blank screen. Participants were required to respond in a maximum responding time of 1200 ms. To control for expectancy effects, the inter-trial interval (ITI) was presented as a red fixation across, and its duration was randomly selected from 800 ms, 1000 ms and 1200 ms, with a mean ITI of 1000 ms.

In the present study, within-trial conflict processing referred to the difference between CI and CC, which provided optimal online within-trial conflict conditions while avoiding the post-conflict cognitive control following incongruent trial (Nigbur et al. 2012). Trial-by-trial conflict processing referred to the conflict sequence effect (CSE, the difference between (CI-CC) and (II-IC)) (Gratton et al. 1992), as in previous studies (Soutschek et al. 2013).

Image acquisition

The DTI data were collected using a 3-Tesla MRI system (General Electric Medical Solutions) at the MR Research Center of Xijing Hospital of the Fourth Military Medical University, Xi'an, in China. Diffusion-weighted sequences with single-shot echo planar imaging in alignment with the anterior-posterior commissural plane were acquired with the following parameters: field of view (FOV) = 240 × 240 mm^2, repetition time (TR)/echo time (TE) = 10,000/82.4 ms, matrix = 128 × 128, slice thickness = 2 mm, and 70 continuous axial slices with no gap. The sequences were repeated in two successive runs with one image at $b = 0$ s /mm^2 and 63 diffusion-weighted images at $b = 1000$ s / mm^2.

Data analysis

Test-retest reliability

Intraclass correlation coefficient (ICC) were calculated as the ratio of between-subjects variance to the sum of the between- and within-subjects variances to assess test-retest reliability (Bartko 1966). The ICC was used to test whether measurement variance was consistent between the two sessions. Stability of ICC values was interpreted using the following standard ranges: "slight" (0.0–0.2); "fair" (0.2–0.4); "moderate" (0.4–0.6); "substantial" (0.6–0.8); and "almost perfect" (0.8–1) (Landis and Koch 1977).

Image analysis

All DTI analyses were performed with FSL 5. 0. 1. The DTI data were corrected for eddy distortions and motion artifacts using the FDT v2.0 (FMRIB's Diffusion Toolbox) (Jenkinson and Smith 2001) function of FSL. FA, AD, RD, and MD images were created by fitting the diffusion tensor to raw diffusion data after brain extraction using the Brain Extraction Tool (Smith 2002). Voxel-wise statistical analyses of the FA data were then carried out using Tract-Based Spatial Statistics (TBSS) v1.2 in FSL (Smith et al. 2006). Briefly, FA images from all subjects were aligned to the FMRIB58_FA standard space using the non-linear registration tool FNIRT (Rueckert et al. 1999). Next, the mean FA image of all subjects was generated and thinned to create a mean FA skeleton (threshold of 0.2), which represents the centers of all tracts common to the group. Each subject's aligned FA data were then projected back onto this skeleton. Similar aligning and analyses were performed on MD, AD, and RD data sampled from voxels with FA > 0.20.

Group statistics were computed separately for FA, MD, AD, and RD included in the WM skeleton on the improvement of the within-trial conflict processing (the difference between the within-trial conflict processing in session 1 and 2) using general linear models (GLM), including sex and age as covariates. Although we did not found a significant correlation between white matter microstructural characteristics and the within-trial conflict processing in session 1, Yamamoto et al. (2015) found a significant correlation between white matter connectivity and response conflict. To eliminate the potential effect of the baseline within-trial conflict processing, within-trial conflict processing in session 1 was also controlled as covariate. Statistical tests were carried out using the FSL tool *randomize* (Winkler et al. 2014), multiple comparisons were corrected through threshold-free cluster-enhanced correction (TFCE correction) (Smith and Nichols 2009). The data were tested against an empirical null distribution generated by 5000 nonparametric permutation-based tests for each contrast (Nichols and Holmes 2002), providing statistical maps that were fully corrected for multiple comparisons across space. Corrected *p*-values <0.05 were considered significant. The JHU ICBM-DTI-81 white-matter label atlas was used to label the significant tracts (Mori et al. 2008).

Finally, lasso regression was used to evaluate the relationship between the white matter microstructural characteristics in significant regions and improvement of the within-trial conflict processing across two sessions. Sex, age, global AD, within-trial conflict processing in the session 1 and AD values from significant regions were vectorized and normalized before entering into a regularized regression model using glmnet (Vilares et al. 2017). Leave-one-out cross validation was used to obtain the optimal regression model and its corresponding L1 regularization value (i.e., λ). The specific approach was as follows:

For each λ, leave-one-out cross validation was used to estimate the performance of the model. Specifically, the validation was conducted at 37 folds, which equaled the number of subjects. In validation fold *i*, thirty-six subjects' data were used as training data for the linear regression while remaining one subject's data (x_i, y_i) were used as test data. Weight vector built from the training data were used to predict the improvement of the test subject $(\hat{y}_i)$. Then $MSE_i = (y_i - \hat{y}_i)^2$ was computed. After repeating this approach 37 times, mean square error $\left(MSE = \frac{1}{37}\sum_{i=1}^{37} MSE_i\right)$ was computed for each λ. The λ that minimizes the *MSE* was selected as the tuning parameter. Finally, all of the observed values and the selected λ were used to re-fit the model.

Results

Trials in which participants failed to respond within the maximum response time, error response trials, trials following an error trial or nonresponse trials, and trials with RTs more than 2.5 SD away from the participant's mean RT for that condition were excluded from analyses.

Effect of session on performance

Effect of session on RT for 83 subjects

Repeated-measures analysis of variance was conducted to examine the effects of three factors, current trial type (congruent vs. incongruent), previous trial type (congruent vs. incongruent), and session (first vs. second), on RT. The results revealed a significant main effect of current trial type ($F_{(1,82)} = 508$, $p = 6.6 \times 10^{-37}$), indicating a significant conflict effect, and significant main effects of previous trial type ($F_{(1,82)} = 26$, $p = 2.1 \times 10^{-6}$) and session ($F_{(1,82)} = 47$, $p = 1.4 \times 10^{-9}$). The mean RTs in session 2 were significantly shorter than those in session 1 (Table 1). We also found an interaction between current and previous trial type ($F_{(1,82)} = 63$, $p = 9.9 \times 10^{-12}$), indicating a significant CSE on RT. There was also a significant interaction between session and current trial type ($F_{(1,82)} = 8.7$, $p = 0.004$). There was no significant interaction between session and previous trial type ($F_{(1,82)} = 0.98$, $p = 0.32$), or between session, previous trial type, and current trial type ($F_{(1,82)} = 0.32$, $p = 0.57$).

Table 1 reports the mean RT under all conditions and the within-trial conflict processing and CSEs, and the results of the variance components analyses (ICC values) and post hoc tests. These results reveal the trait-like characteristics of within-trial conflict processing, CSE and RTs for all conditions. More importantly, the within-trial conflict processing

Table 1 Mean reaction times (RTs) and results of the variance components analyses (ICC values) for 83 subjects

	Session 1		Session 2		Statistical test			
	Mean (ms)	SD	Mean (ms)	SD	*ICC*	*p*	*t*	*p*
CI	497	53	476	43	0.92^{**}	0.000	7.5	7.2×10^{-11}
II	495	50	473	44	0.94^{**}	0.000	8.4	9.5×10^{-13}
IC	430	61	414	50	0.91^{**}	0.000	4.3	4.6×10^{-5}
CC	419	61	405	50	0.94^{**}	0.000	4.4	2.8×10^{-5}
WE	78	31	70	28	0.83^{**}	0.000	3.0	0.003
CSE	13	19	12	17	0.35	0.03	0.57	0.57

CI = congruent followed by incongruent; II = incongruent followed by incongruent; IC = incongruent followed by congruent; CC = congruent followed by congruent; WE = within-trial conflict processing; CSE = conflict sequence effect

and RTs for all conditions in the first session were significantly larger than those in the second session.

Effect of session on RT for 37 subjects

The same repeated-measures analysis of variance was conducted for the subset of 37 subjects. The results revealed a significant main effect of current trial type ($F_{(1,36)} = 181$, $p = 1.2 \times 10^{-15}$), indicating a significant congruency effect, and significant main effects of previous trial type ($F_{(1,36)} = 20$, $p = 7.9 \times 10^{-5}$) and session ($F_{(1,36)} = 18$, $p = 1.4 \times 10^{-4}$). The mean RTs in session 2 were significantly shorter than those in session 1 (Table 2). We also found an interaction between current and previous trial type ($F_{(1,36)} = 37$, $p = 5.2 \times 10^{-7}$), indicating a significant CSE on RT. There was also a significant interaction between session and current trial type ($F_{(1,36)} = 4.5$, $p = 0.04$). There was no significant interaction between session and previous trial type ($F_{(1,36)} = 0.004$, $p = 0.95$) or between session, previous trial type, and current trial type ($F_{(1,36)} = 0.56$, $p = 0.46$).

The results of the variance components analyses (ICC values) and post hoc tests are shown in Table 2 for the mean RTs under all conditions, within-trial conflict processing, and CSE. Similar results were observed. However, test–retest reliability for CSE across the two sessions was not significant, in contrast to the results for the full sample of 83 subjects which observing statistically significant but modest test–retest reliability for CSE. This discrepancy may result from the different samples in the two analyses.

Effect of session on error rates

Repeated-measures analysis of variance was conducted to assess the effects of current trial type (congruent vs. incongruent), previous trial type (congruent vs. incongruent), and session (1 vs. 2) on error rates. The results revealed significant main effects for current trial type (F(1, 82) = 10.1, $p = 0.002$), previous trial type (F(1, 82) = 17.9, $p = 6.1 \times 10^{-5}$), and session (F(1, 82) = 7.3, p = 0.008). There were more errors in session 2 than in session 1 (t(82) = 2.7, $p = 0.008$).The interaction between current and previous trial type was also significant (F(1,82) = 12.3, p = 0.001). There was no significant interaction between session and previous trial type (F(1, 82) = 0.12, $p = 0.73$), session and current trial type (F(1, 82) = 0.32, $p = 0.57$), or session, previous trial type, and current trial type (F(1, 82) = 0.003, p = 0.95). The effect of session on error rate was also analyzed for the subsample of 37 subjects and similar results were observed.

Table 2 Mean reaction times (RTs) and results of the variance components analyses (ICC values) for a subset of 37 subjects

	Session 1		Session 2		Statistical test			
	Mean (ms)	SD	Mean (ms)	SD	*ICC*	*p*	*t*	*p*
CI	501	49	482	39	0.91	4.8×10^{-11}	5.5	5.8×10^{-6}
II	498	46	481	40	0.93	4.2×10^{-13}	6.0	1.3×10^{-6}
IC	435	55	423	47	0.92	5.8×10^{-12}	2.6	0.014
CC	423	58	412	48	0.94	2.5×10^{-14}	2.6	0.013
WE	77	35	69	31	0.90	2.2×10^{-10}	2.2	0.032
CSE	15	19	12	16	0.32	0.13	0.75	0.46

CI = congruent followed by incongruent; II = incongruent followed by incongruent; IC = incongruent followed by congruent; CC = congruent followed by congruent; WE = within-trial conflict processing; CSE = conflict sequence effect

Effect of block on performance

We only present the results for the full sample, as similar results were observed for the subsample.

Effect of block on online within-trial conflict processing

Repeated-measures analysis of variance with current trial type (CI vs. CC) and block (1–5) as two factors and RT as the dependent variable were conducted. The results revealed significant main effects for current trial type (F(1, 82) = 508, $p = 6.6 \times 10^{-37}$) and block (F(4,328) = 9.7, $p = 2.0 \times 10^{-7}$), indicating a general slowing of responses over time. However, there was no significant interaction between block and current trial type (F(4,328) = 0.82, p = 0.5). The effect of block on online within-trial conflict processing was also analyzed for session 2, and similar results were observed. We still observed a general deceleration in responding and no decrease in online within-trial conflict processing across blocks.

We also evaluated whether the effect of block on within-trial conflict processing was modulated by session. Repeated-measures analysis of variance was conducted with current trial type (CI vs. CC), session (session 1 vs. session 2), and block (1–5) as three factors and RT as the dependent variable. The results revealed significant main effects of current trial type (F(1, 82) = 597, $p = 2.1 \times 10^{-39}$), session (F(1, 82) = 44, $p = 3.5 \times 10^{-9}$), and block (F(4, 328) = 12, $p = 2.5 \times 10^{-9}$). The interaction between current trial type and session was also significant (F(1,82) = 8.5, $p = 0.004$). However, there was no significant interaction between block and session (F(4, 328) = 1.6, $p = 0.16$), block and current trial type (F(4, 328) = 0.4, $p = 0.84$), or block, session, and current trial type (F(4, 328) = 0.91, $p = 0.45$).

Effect of block on error rate

Repeated-measures analysis of variance was conducted to analyze the effects of current trial type (CI vs. CC) and block (1–5) on error rate in session 1. The results revealed a significant main effect of current trial type (F(1,82) = 11, $p = 0.001$). There were more errors for CI than for CC (t (82) = 3.3, p = 0.001). However, there was no significant main effect of block (F(4,328) = 1.5, $p = 0.21$) or interaction between block and current trial type (F(4,328) = 0.8, $p = 0.51$). Similar results were observed in session 2. There was a significant main effect of current trial type (F(1,82) = 13.2 $p = 4.8 \times 10^{-4}$), and there were more errors for CI than for CC (t(82) = 3.6, $p = 4.8 \times 10^{-4}$). There was no significant main effect of block (F(4,328) = 1.1, p = 0.4) or interaction between block and current trial type (F(4,328) = 1.3, $p = 0.26$).

Effect of block on conflict adaption effect

Repeated-measures analysis of variance was conducted to analyze the effects of current trial type (congruent vs. incongruent), previous trial type (congruent vs. incongruent), and block (1–5) on RT. The results revealed significant main effects of current trial type (F(1, 82) = 436, $p = 1.4 \times 10^{-34}$), previous trial type (F(1, 82) = 15, $p = 2.0 \times 10^{-4}$), and block (F(4, 328) = 13, $p = 1.4 \times 10^{-9}$). We also found an interaction between current and previous trial type (F(1,82) = 37, $p = 3.2 \times 10^{-8}$). There was no significant interaction between block and previous trial type (F(4, 328) = 0.94, $p = 0.44$), block and current trial type (F(4, 328) = 1.9, $p = 0.1$), or block, previous trial type, and current trial type (F(4, 328) = 2.1, $p = 0.07$). Similar results were observed for the effect of block on CSE in session 2.

Correlation between white matter microstructural characteristics and within-trial conflict processing improvement

Despite the improvement in conflict processing at a group level (Fig. 2), the degree of improvement in the within-trial conflict processing varied greatly across participants (from −29.5 to 42.8). We aimed to evaluate whether individual differences in the degree of improvement in the within-trial conflict processing were related to differences in white matter microstructural characteristics. The voxelwise TBSS results revealed that after controlling for age, sex, and the within-trial conflict processing in session 1, and correcting for multiple comparisons, the improvement in the within-trial conflict processing across the two sessions was positively correlated with AD in the body and splenium of the corpus callosum, right superior and posterior corona radiata, and right SLF (Fig. 3). There were no significant correlations between improvement in the within-trial conflict processing and the other DTI parameters. Furthermore, there was no significant correlation between the within-trial conflict processing in session 1 and the DTI parameters.

The lasso regression results indicated that the AD values in four significant regions and within-trial conflict processing in session 1 accounted for 61% of the variance in the improvement of within-trial conflict processing across the two sessions ($p < 0.0001$) (Table 3). The AD values in the right SLF and corpus callosum were the most important predictors. A permutation test was used to evaluate the significance of the model. The relationship between the normalized predicted and actual improvement in the within-trial conflict processing for the individual subjects is presented in Fig. 3 (Spearman's correlation, $n = 37$).

Finally, to test whether the relationship between the within-trial conflict processing improvement and structural connectivity was selective for the improvement in conflict processing, or whether it was also present in other conditions, we conducted similar lasso regression analyses to examine the relationship between the AD in significant brain regions and the

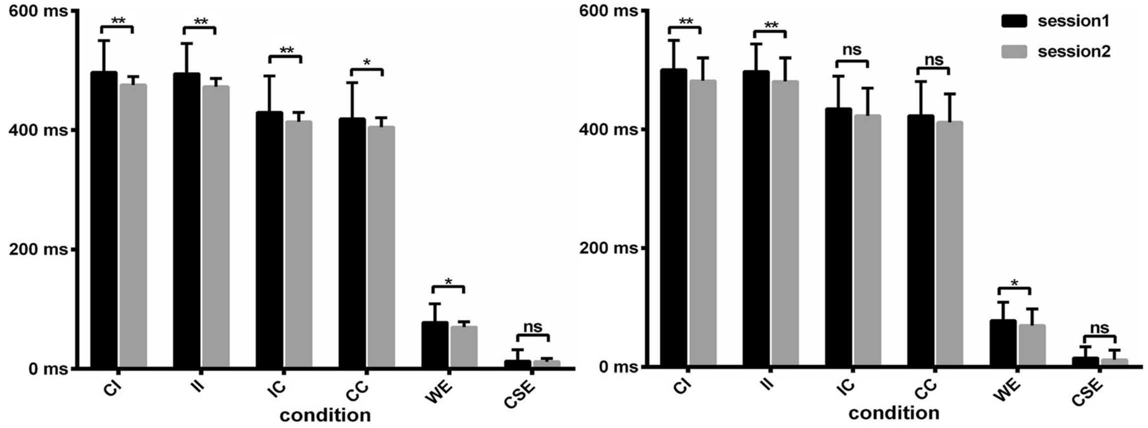

Fig. 2 Improvement of behavior across two session for 83 participant (left) and 37 participants (right). CI = congruent followed by incongruent; II = incongruent followed by incongruent; IC = incongruent followed by congruent; CC = congruent followed by congruent; WE = within-trial conflict processing; CSE = conflict sequence effect

improvement in CC trials across two sessions, reflecting improvement in the simple action of key pressing. The results revealed that the structural-behavioral mapping did not reflect improved CC performance (adjusted $R^2 = 0.12\ p = 0.11$). Thus, we speculate that the relationship between white matter microstructural characteristics and behavioral performance may be selective to improvements in the within-trial conflict processing.

Discussion

Our results showed that at the group level, there was a significant improvement in within-trial conflict processing across two sessions held 2 weeks apart. At the participant level, individual differences were found in the change in the within-trial conflict processing. Furthermore, the degree of improvement in conflict processing between sessions was related to individual differences in white matter microstructural characteristics in tracts sub-serving the visuospatial attention system. These results provide evidence for the hypothesis that individual differences in practice-based within-trial conflict processing improvement can be partially predicted by the underlying white matter microstructural characteristics that sub-serve conflict-related brain regions.

Although the conflict monitoring theory can explain a wide range of results for different congruency tasks, it has been

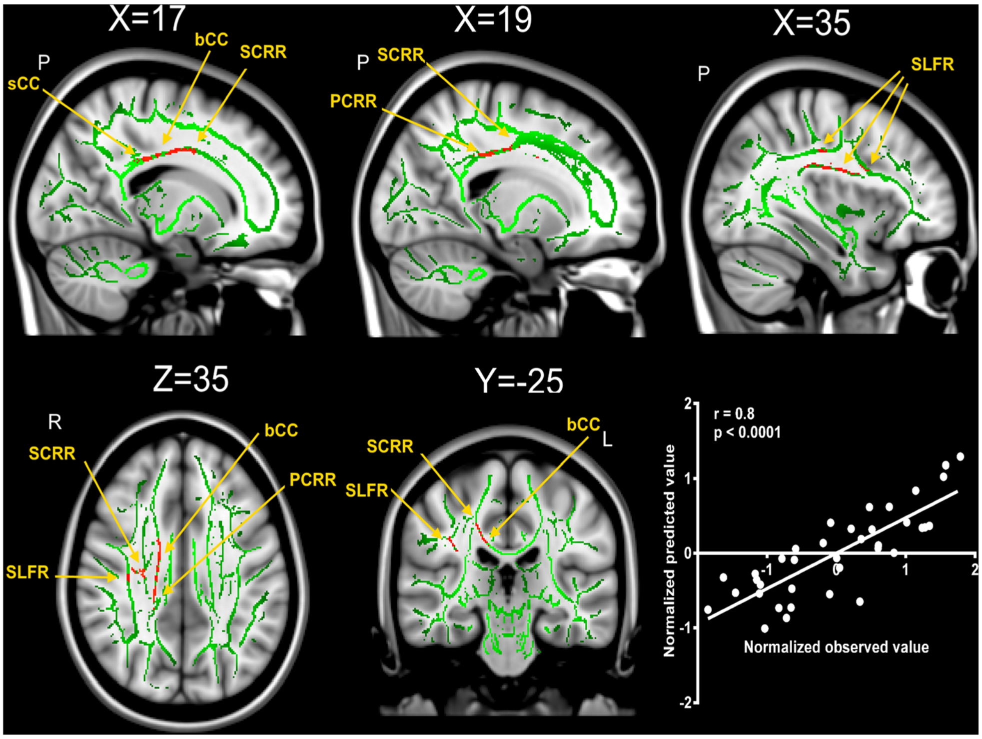

Fig. 3 White matter microstructural characteristics and conflict processing improvement. Corrected for multiple comparisons, the significant brain regions correlated with improvement of conflict processing were located in the body and splenium of the corpus callosum, right superior and posterior corona radiata and right superior longitudinal fasciculus (corrected $p < 0.05$). There was a significant relationship between the predicted and actual improvement of conflict effect for the individual subjects (spearman, $n = 37$)

Table 3 Results of lasso regression

Variable	Beta	*P* value
right SLF	0.29	0.002
sCC	0.19	0.002
bCC	0.18	0.003
Right SCR	0.05	0.03
WE in session 1	0.04	0.02

SLF: superior longitudinal fasciculus; sCC: splenium of the corpus callosum; bCC: body of the corpus callosum; SCR: superior corona radiata; WE: within-trial conflict processing

challenged by two influential alternative accounts, namely feature integration (Mayr et al. 2003; Hommel et al. 2004) and contingency learning (Schmidt and De Houwer 2011; Mordkoff 2012). Numerous modified congruency tasks have been designed to explore the mechanism underlying CSE, with varying results (Schmidt and De Houwer 2011; Duthoo et al. 2014; Kim and Cho 2014; Schmidt and Weissman 2014). Because the present study did not aim to explore the mechanism of CSE, we did not evaluate the relative contribution of attentional and memory-learning accounts. It is possible that these mechanisms interact with each other to produce the CSE.

The high ICC value for the within-trial conflict processing in the present and previous studies may suggest a trait-like characteristic of conflict processing at the within-trial level. The significant but modest test–retest reliability for CSE was consistent with the reliability results reported Feldman and Freitas (2016). The lack of (or weak) trait-like characteristics for CSE indicate that conflict processing at the trial-by-trial level might be more state-dependent. In the present study, although the mean RTs showed significant trait-like characteristics, the RTs in the second session were significantly shorter than those in the first session, which is consistent with previous studies (Clayson and Larson 2013; Feldman and Freitas 2016). More importantly, the within-trial conflict processing in the second session was significantly reduced compared with that in the first session. The reduced within-trial conflict processing may be due to either a decrease in CI and increase in CC, an increase in both CI and CC (where the increase in CC is larger), or a decrease in both CI and CC (where the decrease in CI is larger). Our findings seem to suggest the last of these possibilities: the decreased within-trial conflict processing in the second session was mainly caused by an improvement in the ability to process conflict, rather than in the simple key pressing action.

Similar to the improvement in within-trial conflict processing across the two sessions, a decrease in the congruency effect across blocks in the same session was also expected (Schmidt 2016), which was interpreted by Schmidt et al. as a byproduct of the speedup in responding (i.e., the initially slow incongruent trials gained more from this general speeding up than the initially fast congruency trials) (Schmidt and De Houwer 2016; Schmidt et al. 2016). However, we observed no effect of block on within-trial conflict processing, congruency effect, or error rate. We speculate that there may be two reasons for this discrepancy. First, the pre-experimental practice ran until the subjects successfully completed all trials. This may have allowed contingency learning to stabilize at the beginning of the formal experiment. We cannot confirm this hypothesis because we did not record data for the practice part, but we will do this in future studies. Second, response time across blocks actually slowed in the present study, indicating a fatigue effect, which may counteract the practice effect. Of course, there may be other reasons for this discrepancy. Although block showed no significant effect on within-trial conflict processing, session did show a significant effect, suggesting a practice effect on within-trial conflict processing. However, there was no significant effect of session on trial-by-trial conflict processing. This result is different from the findings of van Steenbergen et al., who found a significant practice effect on CSE (van Steenbergen et al. 2015). It is possible that in their study, feature binding and contingency learning confounds contribute to a substantial part of CSE, which may preclude the interpretation of the practice effect on CSE.

In contrast to the role of the LPFC in representing and maintaining context information (MacDonald et al. 2000), the posterior parietal cortex (PPC), especially in the right hemisphere, participates in activating all competing stimulus-response mapping (Coulthard et al. 2008). The conflict monitoring theory proposes that the MFC detects the response conflict between the potential conflicting responses activated in the right PPC and triggers the attention system to focus on goal-related information and ignore irrelevant information to better resolve the conflict (Botvinick 2001; Corbetta and Shulman 2002; Petersen and Posner 2012). If this is correct, we would expect to see early stage functional connectivity between the MFC and right PPC during the interval between the target stimulus onset and the response. In our previous study, we investigated the functional connectivity between the MFC and PPC using FCz-P3/4 theta (4.5–8 Hz) phase synchronization (Liu et al. 2017). Theta phase synchronization is considered to be a neural communication mechanism that signals the need for control to regions responsible for control, such as the DLPFC (Cavanagh et al. 2009; Cohen and van Gaal 2013; Cavanagh and Frank 2014). As expected, we observed significant functional connectivity between the MFC and right PPC from 200 to 400 ms post-target. More importantly, this functional connectivity was positively correlated with the within-trial conflict processing. These results indirectly support the role of conflict monitoring theory in within-trial conflict processing. More specifically, it has been proposed that conflict processing in flanker tasks is largely dependent on the visuospatial attentional network, which includes the dorsal top-down attention system and the ventral attention system (Petersen and Posner 2012). The dorsal top-down attention system, consisting of the frontal eye fields and intraparietal sulcus/superior parietal lobe, helps to resolve conflicts by controlling the voluntary orientation of attention toward a target location (Gratton et al. 1992; Corbetta et al. 2000; Corbetta and Shulman 2002). The ventral attention system consists of the temporoparietal junction and the ventral frontal cortex. When distractors appear before the target or the target is miscued, the ventral attention system breaks the focus of attention on the distraction and switches it to the target location.

Considering the role of the attention system in conflict processing, we speculate that the attention system may also contribute to the improvement in within-trial conflict processing across the two sessions. This speculation is consent with the findings of other studies that have found that the white matter tracts connecting task-related regions were related to the learning potential in various domains (Floel et al. 2009; Meinzer et al. 2010; Wong et al. 2011). For example, the microstructural characteristics of the white matter tracts connecting brain regions associated with auditory language processing can be used to predict individual differences in responsiveness to training on sound-to-word learning paradigms (Wong et al. 2011). As expected, the features that predicted the improvement across two sessions were located in the white matter microstructural characteristics connecting the visuospatial attention system and bilateral hemispheres. The high correlation between predicted improvement and actual improvement indicates a high prediction accuracy rate.

The two features that contributed most were the right SLF (i.e., the association pathway sub-serving the visuospatial attentional network) and the corpus callosum (i.e., the bundle of commissural fibers that enable communication between the hemispheres). Anatomically, the three branches of the SLF (I–III) interconnect the visuospatial attentional networks. SLFIsupports the dorsal attention system, SLFIIinterconnects the dorsal and ventral networks, and SLF III subserves the ventral attention system (Chechlacz et al. 2015). Studies have demonstrated the important role of the SLF in visuospatial attention. For example, individual differences in the structural organization of the SLF are related to the response of the visuospatial attention system to transcranial magnetic stimulation over the right intraparietal sulcus (Cazzoli and Chechlacz 2017). Studies have also proposed a significant role for the corpus callosum in visuospatial attention. The fibers of the corpus callosum project into prefrontal, premotor, and supplementary motor regions and other posterior regions of the cortex (Witelson 1989) and facilitate inter-hemispheric communication (Gazzaniga 2000). In incongruent trials on the flanker task, both the target and the distractor activate the motor cortex of the corresponding hemisphere before the subject's response (Verleger et al. 2009), and the incorrect activation precedes the correct activation. Inter-hemispheric response conflict is induced when the incorrect response and the correct response are mapped to different hands. Visuospatial attention may enhance and balance the inter-hemispheric communication through the corpus callosum to resolve the asymmetric influence of the incorrect response on the correct response (Wang et al. 2016). This asymmetric influence may be derived from the asymmetric cooperation of each hemisphere in spatial perception, which shares similar brain circuits to spatial attention. We speculate that the corpus callosum may also facilitate cooperation within the dorsal attention system, which is organized bilaterally.

We found a positive correlation between AD and the degree of improvement in the within-trial conflict processing. In contrast to RD, which reflects the degree of myelination, AD reflects the strength of anisotropic diffusion along axons and has been shown to correlate positively with microscopy-derived axon density and diameter (Takagi et al. 2009). The relationship between AD and behavior might indicate that differences in axonal morphology across individuals result in differences in the improvement of the within-trial conflict processing. This seems reasonable considering the role of AD in controlling the speed of impulse conduction between distant regions, which is critical for learning. However, more animal studies are necessary to confirm this hypothesis. The correlations between AD values in the SLF and corpus callosum and the improvement in the within-trial conflict processing support the hypothesis that white tracts connecting the visuospatial attentional networks predict the degree of within-trial conflict processing improvement across two sessions. This effect was mainly seen in the right hemisphere, which we suspected may be a result of the influence of hemispheric specialization in visuospatial attention (Thiebaut de Schotten et al. 2011).

Our study provides strong evidence that at the group level, the ability of within-trial conflict processing can be improved by practice. Importantly, the white matter microstructural characteristics of the tracts connecting the visuospatial attention system, which plays an important role in conflict processing, can be used to predict the degree of improvement in conflict processing. The significant relationship between individual differences in the improvement in within-trial conflict processing and the underlying white matter structure suggest that the backbone of the task-related network may predict the practice-based improvement in task performance. These findings may provide clues to the brain mechanism underlying individual differences in the improvement response to practice, and facilitate the development of cognitive control training and intervention programs. The study also has some limitations. First, the sample in the present study was small. Second, the participants only completed two behavioral sessions, which may differ from standard learning paradigms. In a future study, we will test the brain mechanism underlying the efficient learning of conflict processing using a larger sample and standard learning paradigms.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declarations and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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