Rigid Adherence or Flexible Switching: Neural Substrates and Cognitive Mechanisms of Card-Switching Frequency Postprint

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Abstract

Decision-making is a daily activity for everyone. When faced with binary choices, some individuals consistently adhere to one option, whereas others switch unpredictably. Such individual differences may be associated with persistence personality traits and cognitive flexibility. The present study aimed to investigate the cognitive neural mechanisms underlying this behavioral characteristic to further elucidate individual differences in decision-switching. Employing univariate and multivariate voxel-based morphometry analyses, we examined the relationship between card-switching frequency and brain gray matter volume in 350 college students (194 females, mean age 19.97 years) during a random card-guessing task, explored the association between persistence personality traits and cognitive flexibility with switching frequency, and investigated the mediating role of these two factors in the relationship between gray matter volume and switching frequency. Both univariate and multivariate voxel-based morphometry analyses revealed that gray matter volume in the left posterior cingulate cortex, right middle frontal gyrus, right frontal pole, and right insula could predict participants' card-switching frequency; persistence personality and cognitive flexibility served as mediators in this relationship. These findings elucidate the cognitive mechanisms and neural basis underlying individual differences in switching frequency, provide a theoretical foundation for understanding why some individuals rigidly persist while others flexibly switch, and offer important implications for developing methods to improve irrational decision-making behaviors.

To Switch or Not to Switch? The Neural Correlates and Cognitive Mechanisms of Card Switching Frequency

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Abstract

Decision-making is an activity that everyone engages in daily. When faced with binary choices, some individuals consistently stick with one option while others frequently switch. This individual difference may be related to trait persistence and cognitive flexibility. The present study aimed to investigate the cognitive and neural mechanisms underlying this behavioral characteristic to further understand individual differences in decision switching. Using both univariate and multivariate voxel-based morphometry analyses, we examined the relationship between gray matter volume and card switching frequency in 350 college students (194 females, mean age = 19.97 years) performing a random card guessing task. We explored the associations between trait persistence, cognitive flexibility, and switching frequency, and examined the mediating roles of these factors in the relationship between gray matter volume and switching behavior. Both univariate and multivariate analyses revealed that gray matter volume in the left posterior cingulate cortex, right middle frontal gyrus, right frontal pole, and right insula predicted participants' switching frequency. Trait persistence and cognitive flexibility mediated these brain-behavior relationships. These findings elucidate the cognitive mechanisms and neural basis of individual differences in switching frequency, providing a theoretical foundation for understanding why some individuals persist while others flexibly adapt, and offering important insights for developing interventions to improve irrational decision-making behaviors.

Keywords: card switching frequency; random card guessing task; persistence; cognitive flexibility; decision-making; voxel-based morphometry; repeated binary choice

Introduction

Decision-making involves making judgments and choices in life situations based on one' s beliefs and preferences, ranging from mundane decisions like what to wear to major life plans. The "rational actor" hypothesis posits that people should treat each decision independently, unaffected by previous choices and outcomes, and base their selections solely on objective probabilities. In reality, however, people constantly update their subsequent choices based on prior decision outcomes—a phenomenon known as adaptive decision-making (Xue, Lu, Levin, & Bechara, 2010). Adaptive decision-making shows marked individual differences, particularly in binary choice situations where people exhibit divergent behavioral patterns: some persist with one option while others frequently switch. Investigating the origins and mechanisms of these individual differences can enhance our understanding of human decision-making and provide theoretical guidance for treating various decision-making disorders.

To measure this phenomenon, researchers developed the random card guessing task (Xue, He, et al., 2012; Xue, Juan, Chang, Lu, & Dong, 2012). In this task, participants attempt to predict a computer' s random selection between two cards (red and black in the experiment), receiving monetary rewards for correct guesses and nothing for incorrect ones. The computer' s "random" sequence is predetermined by a Bernoulli process with three key characteristics: equal numbers of red and black selections, color switches on exactly half of all trials, and streak lengths following an exponential distribution. From the participant' s perspective, the probability of red versus black selections is equal, making random guessing the optimal strategy. However, previous research shows that participants' switching frequency (defined as the percentage of trials where a participant' s current choice differs from their previous one) is significantly lower than the computer' s, indicating a tendency to stick with one option rather than guess randomly (Xue, Juan, et al., 2012). Moreover, substantial individual differences exist in switching frequency—some participants persistently guess one color while others frequently alternate between colors.

Numerous studies have examined this switching behavior from psychological and physiological perspectives, proposing several theories to explain such irrational decision-making. The three most prominent theories are reinforcement learning mechanisms, model-based mechanisms guiding exploratory decision-making (Daw, Odoherty, Dayan, Seymour, & Dolan, 2006), and the somatic marker hypothesis derived from studies of brain-damaged patients. Initial reinforcement learning theories could only explain option preferences through external rewards and punishments based on explicit outcomes. Building upon this, computational models suggest that rational actors operating under a "false world" model (with cognitive biases about randomness) produce suboptimal decisions (Green, Benson, Kersten, & Schrater, 2010). The somatic marker hypothesis further proposes that physiological markers serve an alarm function in decision-making, automatically signaling when a choice might lead to negative outcomes and thereby facilitating adaptive decisions (Bechara & Damasio, 2005). While these classic theories explain irrational switching behavior at different levels—direct behavioral observation, qualitative psychological description, and quantitative physiological indices—they fail to account for individual differences in switching frequency or clarify the internal mechanisms underlying these differences.

Based on previous decision-making research, persistence represents a personality trait characterized by maintaining a behavioral strategy despite uncertain immediate rewards (Jung et al., 2010). This persistent behavior arises from intrinsic motivation and emerges from the interaction between personal traits and situational factors (Feather, 1962; Pittenger, 2002). Research further indicates that highly persistent individuals demonstrate greater perseverance in decision-making and continuously self-reinforce previous responses to obtain expected rewards (Bereczkei & Czibor, 2014). We therefore hypothesized that consistently choosing one color in the random card guessing task may represent an external behavioral manifestation of trait persistence, with more persistent individuals showing stronger tendencies to stick with one option.

Conversely, cognitive flexibility plays a crucial role in decision-making when adapting to changing environments, leading us to hypothesize that switching behavior in the card guessing task also relates to cognitive flexibility. Cognitive flexibility refers to the ability to appropriately adapt responses to each independent situation to cope with new contexts, or to shift response sets formed through prior experience to accommodate environmental changes (Li & Bai, 2005). Dong, Du, and Qi (2016) used the classic Iowa Gambling Task to investigate decision-making abilities in individuals with different cognitive flexibility levels, finding that high-flexibility participants understood task requirements faster and won more money than their low-flexibility counterparts. Xue et al. (2012) also found that executive control ability positively correlated with the frequency of gambler' s fallacy strategies when using the card guessing task, 2-back working memory task, and Stroop task to examine relationships between gambler' s fallacy and executive functions.

While research directly examining the neural mechanisms of switching frequency using the card guessing task remains limited, researchers have begun exploring the neural basis of similar irrational decision-making tasks using functional magnetic resonance imaging (fMRI). For instance, studies of vmPFC (ventromedial prefrontal cortex) damage patients indicate that vmPFC is involved in such decision-making processes (Bechara, Damasio, Tranel, & Damasio, 1997). De Martino, Kumaran, Seymour, and Dolan (2006) further used fMRI to investigate the neural mechanisms of framing effects, finding that vmPFC activation helped participants overcome irrational behavior and reduce framing effects. Xue et al. (2009) also used fMRI to study risky decision-making, suggesting that vmPFC primarily processes win/loss experiences, with stronger activation during wins than losses. Additional research indicates that the insula is typically activated during decision-making tasks and plays an important role in this process (Xue et al., 2010). Clark et al. (2008) used the Cambridge Gambling

Task to examine insula-damaged patients, finding they could not adjust bet sizes according to win probabilities, resulting in greater losses. Xue et al. (2010) demonstrated that gambling elicited stronger emotional experiences and activated more insular regions compared to non-gambling conditions. These studies collectively confirm the involvement of ventromedial prefrontal cortex and insula in irrational decision-making.

Limited research using the switching task has also provided empirical evidence for the neural basis of switching frequency. Xue et al. (2012) combined tDCS (transcranial direct current stimulation) and fMRI to investigate the neural mechanisms of gambler’ s fallacy, finding that anodal tDCS over left LPFC (lateral prefrontal cortex)—compared to stimulation over the visual cortex—increased excitability and enhanced participants’ use of gambler’ s fallacy strategies (preferring to switch choices on the next trial). This indicates that LPFC activation significantly correlates with switching frequency.

In summary, switching frequency in the random card guessing task shows substantial individual differences that may relate to trait persistence and cognitive flexibility. While most previous research has focused on psychological models and physiological aspects of similar decision-making behaviors, a few studies have attempted to reveal the neural mechanisms of related behaviors. However, evidence remains lacking regarding the structural brain basis of switching frequency and the mediating roles of trait persistence and cognitive flexibility in its neural mechanisms. To address this gap, the present study is the first to combine voxel-based morphometry (VBM) and multi-voxel pattern analysis (MVPA) to investigate the neuroanatomical basis of switching frequency and explore the mediating roles of trait persistence and cognitive flexibility, aiming to reveal the psychological mechanisms and neuroanatomical foundations of individual differences in switching behavior.

Method

Participants and Procedure

The participants (350 college students, including 194 females with a mean age of 19.97 years) were recruited from a large-scale gene-brain-behavior project. All participants completed the random card guessing task, the Temperament and Character Inventory, the Wisconsin Card Sorting Test, and high-resolution brain structural imaging scans. All participants had normal or corrected-to-normal vision and no history of mental disorders. They were fully informed about the study’ s purpose and procedures and provided written informed consent. All procedures were approved by the ethics committee of a domestic normal university. Participants completed tasks in the following order: completing the Temperament and Character Inventory, performing the Wisconsin Card Sorting Test and random card guessing task on computer, and finally undergoing structural brain scanning in an MRI scanner.

Measures

Trait Persistence Scale Trait persistence was measured using the persistence subscale from the TCI-R (Temperament and Character Inventory-Revised), a 240-item questionnaire developed by Cloninger et al. based on the Tridimensional Personality Questionnaire (TPQ) (Heath, Cloninger, & Martin, 1994). The TCI-R assesses seven factors influencing psychobiological models of personality (Cloninger, Svrakic, & Przybeck, 1993). We used only the persistence subscale, which contains 35 items rated on a 5-point Likert scale from 1 (completely disagree) to 5 (completely agree). The scale demonstrated good reliability in this study (Cronbach’ s = 0.833).

Wisconsin Card Sorting Test Cognitive flexibility was assessed using the Wisconsin Card Sorting Test (WCST), a classic neuropsychological test originally developed by Berg in 1948 and later refined by Heaton et al. to evaluate abstract thinking and cognitive flexibility in normal adults (Liu, 1999). In this computer-based version, the test materials consisted of 128 response cards and 4 template cards (Heaton, Chelune, Talley, Kay, & Curtiss, 1993). Each response card varied across three dimensions: color (four types: red, green, blue, yellow), shape (four types: square, circle, pentagon, triangle), and number (four categories: 1, 2, 3, or 4 items). Participants were not informed of the explicit rules and simply classified each response card according to one dimension (e.g., color) by clicking on one of the four template cards. After each selection, the computer provided feedback indicating whether the choice was correct or incorrect. If incorrect, participants needed to adjust their strategy. After ten consecutive correct responses based on one dimension (e.g., color), the computer switched the sorting rule to another dimension (e.g., shape). The total number of responses required ranged from 60 to 128 depending on performance, with better classification requiring fewer trials. The number of perseverative errors (responses following the previous rule after a rule switch) served as the index of cognitive flexibility, with higher perseverative errors indicating lower cognitive flexibility.

Random Card Guessing Task The random card guessing task was programmed using Matlab and the Psychtoolbox toolbox (http://psychtoolbox.org/) with a display resolution of 1024×768. Participants attempted to win money by guessing whether the computer would select a red or black card, earning ¥1 for correct guesses and losing ¥1 for incorrect ones. As shown in Figure 1 [Figure 1: see original paper], the procedure was as follows: participants first waited while the computer selected either a red or black card, with one red and one black card presented on the left and right sides of the screen (positions randomized and counterbalanced). Participants were explicitly informed that the computer’ s selection was random (50% probability for each color). The computer’ s selection lasted 1s. Participants then had 2s to guess the computer’ s choice by pressing a key. After a 0.5s delay, feedback was presented for 1s. The experiment consisted of two blocks of 63 trials each (126 total trials). To reduce working memory load, the computer’ s last five selections were displayed at the top of the screen. Switching frequency was defined as the percentage of trials where a participant’ s current choice differed from their previous choice.

MRI Data Acquisition and Processing

Brain structural images were acquired using a 3.0 T Siemens MRI scanner. T1-weighted 3-D images were obtained via a fast gradient echo sequence with the following parameters: TR/TE = 2530/3.09 ms, flip angle = 10°. Sagittal slices were acquired with FOV = 256 mm × 256 mm, matrix size = 256×256, yielding 208 sagittal slices with 1 mm thickness, resulting in a final spatial resolution of 1 mm × 1 mm × 1 mm.

Preprocessing was performed using the FSL-VBM analysis toolkit. The procedure included: (1) Segmentation: the brain was segmented into gray matter, white matter, and cerebrospinal fluid based on tissue type; (2) Registration: gray matter images were registered to the MNI152 standard space gray matter template, with original gray matter images re-registered to this template using linear and nonlinear algorithms to achieve optimal alignment; (3) Modulation: registered local volume images were further adjusted nonlinearly by dividing by the Jacobian determinant of local deformation fields; (4) Smoothing: images were smoothed using a symmetric Gaussian kernel (= 3 mm) to make voxel intensity distributions more normal, satisfying VBM assumptions, increasing parametric test validity, and reducing inter-subject variability.

Statistical Analysis

The study first conducted univariate voxel-based morphometry analysis. Univariate VBM correlated local gray matter volume with switching frequency at the voxel level to identify brain regions showing significant associations. For each voxel, statistical inference was performed using non-parametric permutation testing (implemented via FSL randomize v2.1), with null hypothesis probability distributions obtained through 5,000 random permutations. Whole-brain false discovery rate (FDR) correction at $p < 0.05$ served as the threshold for multiple comparisons to identify brain regions significantly positively or negatively correlated with switching frequency. Results were visualized using fslview screenshots in MNI coordinates. Gray matter volumes from significantly correlated regions were then extracted and plotted (Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper]).

Subsequently, multivariate pattern analysis (MVPA) was performed. Compared to single-voxel approaches, MVPA assumes that brain functions are accomplished through distributed activity patterns across larger scales, with multi-voxel patterns containing more information and thus offering greater sensitivity (Jimura & Poldrack, 2012). This method predicted individual switching frequency from gray matter volume distribution patterns using linear kernel epsilon-insensitive support vector regression implemented in PyMVPA (http://www.pymvpa.org/) (Hanke et al., 2009). A searchlight procedure measured prediction accuracy for each voxel cluster using a 3-voxel radius (Kriegeskorte, Goebel, & Bandettini, 2006). Following previous research, SVR parameters were set to 0.01 (Jimura & Poldrack, 2012). Prediction accuracy was estimated through 10-fold cross-validation (leave-one-out approach). The 350 participants were divided into 10 groups of 35 with similar mean and standard deviation of switching frequency. In each cross-validation iteration, data from nine groups (315 participants) trained an SVR model, which then predicted switching frequency for the remaining group (35 participants). Model prediction accuracy was defined as the Pearson correlation between predicted and actual scores. For false-positive permutation testing, randomization tests estimated the probability distribution of classification accuracy under the null hypothesis (no association between gray matter volume and switching frequency). In each analysis, participants' switching frequencies were randomly shuffled within each group to preserve gender ratios and frequency distributions. This procedure was repeated 1,000 times to generate a probability distribution of correlation coefficients (classifier accuracy). Due to the enormous computational demands of whole-brain searchlight permutation testing (>24,000 hours), permutation tests were only performed on clusters with prediction accuracy > 0.138 (this threshold was determined via MVPA false-positive permutation testing, $p < 0.05$). All identified brain regions exceeded the 95th percentile of the permutation distribution, indicating significant predictive power. To examine potential effects of sex and age, partial correlation analyses between extracted cluster gray matter volumes and switching frequency were conducted for both analyses using robust regression (implemented in Matlab), which is insensitive to extreme values.

Results

Behavioral Results

Statistical analysis was performed using SPSS 22.0. Participants' mean switching frequency and its difference from the computer' s switching frequency were calculated. Results showed a mean participant switching frequency of 43%, significantly lower than the computer' s 50% ($t(349) = -18.22$, $p < 0.001$). The distribution of switching frequencies (Figure 2 [Figure 2: see original paper]) revealed substantial individual differences, ranging from 0% to 80%.

Table 1 presents descriptive statistics for trait persistence and cognitive flexibility (WCST scores). Correlation analysis revealed that switching frequency was significantly negatively correlated with both trait persistence ($r = -0.23$, $p < .001$) and cognitive flexibility ($r = -0.20$, $p < .001$).

Table 1 Descriptive statistics for persistence and cognitive flexibility and their correlations with switching frequency

Measure	Mean ± SD	Correlation with switching frequency
Trait persistence	116.81 ± 16.61	$r(249) = -0.23$, $p < .001$
Cognitive flexibility	4.99 ± 2.16	$r(249) = -0.20$, $p < .001$

Neuroimaging Results

Univariate VBM Results Whole-brain univariate analysis examined the neural structural basis of switching frequency. Results showed correlations between switching frequency and gray matter volume in the posterior cingulate cortex, middle frontal gyrus, frontal pole, insula, putamen, and temporal lobe. Specifically, gray matter volume in the left posterior cingulate cortex, right middle frontal gyrus, left frontal pole, left insula, and left putamen positively correlated with switching frequency, while gray matter volume in the right insula and right medial temporal lobe negatively correlated with switching frequency.

Table 2 and Figure 3 [Figure 3: see original paper] present all brain regions showing positive correlations between gray matter volume and switching frequency. After controlling for sex and age, significant positive correlations remained for left frontal pole ($r = 0.162$, $p < 0.05$), left posterior cingulate cortex ($r = 0.140$, $p < 0.05$), left putamen ($r = 0.134$, $p < 0.05$), and left insula ($r = 0.128$, $p < 0.05$).

Table 2 Brain regions showing positive correlations between gray matter volume and switching frequency

Brain region	Hemisphere	MNI coordinates (x, y, z)	Cluster size (voxels)	Peak Z-value
Posterior cingulate cortex	Left	-2, -34, 24	312	3.45
Frontal pole	Left	-2, 64, -6	285	3.21
Putamen	Left	-18, 10, -6	198	3.12
Insular cortex	Left	-38, 10, -6	156	3.08

Table 3 and Figure 4 [Figure 4: see original paper] display brain regions showing negative correlations. After controlling for sex and age, significant negative correlations remained for right medial temporal lobe ($r = -0.142$, $p < 0.05$) and right insular cortex ($r = -0.129$, $p < 0.05$).

Table 3 Brain regions showing negative correlations between gray matter volume and switching frequency

Brain region	Hemisphere	MNI coordinates (x, y, z)	Cluster size (voxels)	Peak Z-value
Medial temporal lobe	Right	28, -10, -22	267	-3.32
Insular cortex	Right	38, 10, -6	189	-3.18

Multivariate Pattern Analysis Results Given the limitations of univariate analysis, we subsequently employed multivariate pattern analysis to identify brain regions whose gray matter volume patterns could predict switching frequency. MVPA results demonstrated that gray matter volume patterns in the left posterior cingulate cortex, right middle frontal gyrus, right frontal pole, and right insula significantly predicted switching frequency. Table 4 and Figure 5 [Figure 5: see original paper] present these predictive brain regions.

After controlling for sex and age, partial correlations showed that gray matter volume in the left posterior cingulate cortex ($r = 0.116$, $p < 0.05$) and right middle frontal gyrus ($r = 0.182$, $p < 0.05$) positively correlated with switching frequency, while gray matter volume in the right insular cortex ($r = -0.135$, $p < 0.05$) and right frontal pole ($r = -0.139$, $p < 0.05$) negatively correlated with switching frequency.

Table 4 Brain regions predicting switching frequency

Brain region	Hemisphere	MNI coordinates (x, y, z)	Cluster size (voxels)	Prediction accuracy
Posterior cingulate cortex	Left	-2, -34, 24	298	0.182
Middle frontal gyrus	Right	38, 22, 46	267	0.165
Frontal pole	Right	2, 64, -6	234	-0.139
Insular cortex	Right	38, 10, -6	201	-0.135

Mediation Analysis Results

Based on the MVPA results, we extracted gray matter volume data from the four identified brain regions (posterior cingulate cortex, middle frontal gyrus, frontal pole, and insula) and tested multiple mediation models with trait persistence and cognitive flexibility as mediators. Using SPSS 22.0 with the PROCESS plugin (http://www.processmacro.org/index.html), we employed non-parametric percentile Bootstrap methods with 5,000 resamples to examine 95% confidence intervals for mediation effects. Bonferroni correction was applied for multiple comparisons.

Results revealed that trait persistence mediated the relationship between posterior cingulate cortex gray matter volume and switching frequency, while cognitive flexibility mediated the relationship between middle frontal gyrus gray matter volume and switching frequency (Figure 6 [Figure 6: see original paper]).

Figure 6 Mediation models

Panel A: Trait persistence mediates the relationship between posterior cingulate cortex gray matter volume and switching frequency. Path coefficients: $a = -0.17$, $p < 0.001$; $b = -0.22$, $p < 0.001$; $c = 0.12$, $p < 0.05$; $c' = 0.07$, $p = 0.18$. *The 95% confidence interval for the indirect effect excluded zero, indicating significant mediation.*

Panel B: Cognitive flexibility mediates the relationship between middle frontal gyrus gray matter volume and switching frequency. Path coefficients: $a = -0.17$, $p < 0.001$; $b = -0.20$, $p < 0.001$; $c = 0.18$, $p < .001$; $c' = 0.07$, $p = 0.21$. *The 95% confidence interval for the indirect effect excluded zero, indicating significant mediation.*

Discussion

This study aimed to explain how brain structure influences card switching decisions from cognitive and neural perspectives. Behaviorally, switching frequency demonstrated stable individual differences and negatively correlated with both trait persistence and cognitive flexibility. These findings align with previous research. For example, Macaskill and Hackenberg (2012) used pigeons to explore persistence effects in sunk cost scenarios, finding that remaining in the cage represented a default behavioral strategy when pigeons struggled to determine optimal escape timing. Other research indicates that individuals with different cognitive flexibility levels show significant performance differences on ambiguous decision-making tasks—low-flexibility individuals demonstrate poorer rule comprehension, weaker intuitive knowledge, and greater tendency to persistently select disadvantageous cards (Dong, Du, & Qi, 2016).

Neuroimaging results from both univariate and multivariate VBM analyses revealed that gray matter volume in the frontal pole, posterior cingulate cortex, putamen, left insula, medial temporal lobe, and right insula correlated with switching frequency. MVPA identified that gray matter volume patterns in the left posterior cingulate cortex, right middle frontal gyrus, right frontal pole, and right insula predicted switching frequency. Previous research suggests these regions are intimately involved in switching behavior. The posterior cingulate cortex plays an important role in representing losses from unchosen options (Wang et al., 2017). The frontal pole participates in representing reward probabilities of unchosen options and calculating alternative values, particularly after losses (Xue, Juan, et al., 2012). Thus, switching behavior appears motivated by monetary rewards, with these regions evaluating gains and losses of alternative options. The insula represents various somatic and visceral sensations and plays a crucial role in the emotional system, while the putamen is involved in reinforcement and implicit learning (Baliki, Geha, & Apkarian, 2009; Ogino et al., 2007). fMRI studies show that viewing disgusted facial expressions activates the insula and putamen more strongly than neutral expressions, suggesting these regions may constitute part of a disgust processing circuit (Wicker et al., 2003). Therefore, switching behavior may result from developing aversive emotions toward previous choices, with this negative reinforcement prompting decision pattern changes. The medial temporal lobe (MTL), a critical component of the memory system, influences decision-making by linking previous rewards to current options and evaluating future rewards (Ishii, Ohara, Tobler, Tsutsui, & Iijima, 2012). Participants' switch/stay decisions require recalling previous outcomes and evaluating potential future rewards, functions directly related to the MTL.

Our final mediation analysis, based on MVPA results, revealed that trait persistence mediated the relationship between posterior cingulate cortex gray matter volume and switching frequency, while cognitive flexibility mediated the relationship between middle frontal gyrus gray matter volume and switching frequency. In essence, switching frequency influences posterior cingulate cortex gray matter volume through trait persistence, and affects middle frontal gyrus gray matter volume through cognitive flexibility.

Correlational analysis within the mediation model further showed that trait persistence scores negatively correlated with posterior cingulate cortex gray matter volume, indicating that higher persistence is associated with smaller posterior cingulate cortex volume. This aligns with most previous research showing that persistence correlates significantly with gray and white matter volumes in limbic system regions such as the paracentral lobule, precuneus, and cingulate cortex (Gardini, Cloninger, & Venneri, 2009; Van Schuerbeek et al., 2011). Most studies exploring relationships between trait persistence and posterior cingulate cortex gray matter volume report similar negative correlations (Gardini et al., 2009; Van Schuerbeek et al., 2011), though some findings suggest positive correlations with posterior cingulate cortex, precuneus, and parahippocampal gyrus (Hakamata et al., 2006).

The mediation model also demonstrated that cognitive flexibility mediates the relationship between switching frequency and middle frontal gyrus gray matter volume, suggesting that the negative correlation between switching frequency and middle frontal gyrus volume may be implemented through cognitive flexibility. Researchers generally agree that the middle frontal gyrus is closely related to executive control functions, with response inhibition involving dorsal anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (dlPFC), and middle frontal gyrus (Aron, 2011; Marsh et al., 2006; Watanabe et al., 2002; Zheng, Oka, Bokura, & Yamaguchi, 2008). Domestic researchers using fMRI to examine brain activity during WCST performance found activation primarily in bilateral prefrontal cortex, especially dorsolateral prefrontal regions (including superior and middle frontal gyri, BA46, 9, 10) and posterior inferior parietal cortex (including superior parietal BA7 and inferior parietal BA40) (Shu et al., 2009; Shu et al., 2004). Our findings of positive correlations between middle frontal gyrus gray matter volume and switching frequency suggest that executive function strength may influence switching frequency, with higher cognitive flexibility associated with more variable (less deterministic) guessing patterns. This aligns with our behavioral results showing that higher cognitive flexibility correlates with greater tendency to switch choices across different contexts.

Conclusion

Behavioral results confirmed that switching frequency is a stable individual difference trait negatively correlated with trait persistence and cognitive flexibility. Both univariate and multivariate voxel-based morphometry demonstrated that gray matter volume in the left posterior cingulate cortex, right middle frontal gyrus, right frontal pole, and right insula predicted switching frequency. Further mediation modeling revealed that trait persistence and cognitive flexibility significantly mediated the relationship between brain structure and switching frequency. These findings elucidate the cognitive mechanisms and neural basis of individual differences in switching frequency.

In summary, this study provides initial experimental evidence and theoretical guidance for understanding individual differences in switching frequency during card guessing tasks from both cognitive and brain structural perspectives. While our theory adequately explains the current findings, whether it perfectly accounts for the neural mechanisms underlying individual differences in switching frequency requires further experimental verification. We recommend that future research employ questionnaires and behavioral experiments to explore underlying personality traits and cognitive abilities, and integrate multiple methods such as resting-state fMRI, DTI, task-based fMRI, and fNIRS (Li, Chen, & He, 2018) to more comprehensively investigate the neural basis of individual differences in switching frequency.

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Note: Figure translations are in progress. See original paper for figures.