Convergent creative thinking performance is associated with white matter structures: Evidence from a large sample study

Hikaru Takeuchi a,*, Yasuyuki Taki a, b, c, Izumi Matsudaira c, Shigeyuki Ikeda d, Kelsy H. dos S. Kawata e, f, Rui Nouchi g, h, i, Kohei Sakaki i, Seishu Nakagawa f, j, Takayuki Nozawa k, Susumu Yokota i, Tsuyoshi Araki i, Sugiko Hanawa i, Ryo Ishibashi f, m, Shohei Yamazaki i, Ryuta Kawashima a, d, i

a Division of Developmental Cognitive Neuroscience, Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan
b Division of Medical Neuroimaging Analysis, Department of Community Medical Supports, Tohoku Medical Megabank Organization, Tohoku University, Sendai, Japan
c Department of Radiology and Nuclear Medicine, Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan
d Department of Ubiquitous Sensing, Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan
e Center for Evolutionary Cognitive Sciences, The University of Tokyo, Tokyo, Japan
f Department of Human Brain Science, Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan
g Creative Interdisciplinary Research Division, Frontier Research Institute for Interdisciplinary Science, Tohoku University, Sendai, Japan
h Human and Social Response Research Division, International Research Institute of Disaster Science, Tohoku University, Sendai, Japan
i Advanced Brain Science, Institute of Development, Aging and Cancer, Tohoku University, Sendai, Japan
j Department of Psychiatry, Tohoku Pharmaceutical University, Sendai, Japan
k Research Center for the Earth Inclusive Sensing Empathizing with Silent Voices, Tokyo Institute of Technology, Tokyo, Japan
l Faculty of Arts and Science, Kyushu University, Fukuoka, Japan
m Smart-Aging Research Center, Tohoku University, Japan

ARTICLE INFO

Keywords:
Convergent thinking
Remote associates
Structural connectivity
Voxel-based morphometry
Diffusion tensor imaging

ABSTRACT

In laboratory settings, creativity is measured using tasks of divergent as well as convergent thinking. It has been suggested that brain connectivity is important for creativity. In the present study, we investigated the associations of convergent thinking performance of compound Remote Associates Test (CRAT) with fractional anisotropy (FA) in diffusion tensor imaging and regional white matter (WM) volume (rWMV) in voxel-based morphometry in a large sample of healthy young adults (360 males and 280 females; mean age: 20.9 years, SD = 1.6). We showed that CRAT performance was positively correlated with WM pathway property (i.e., FA) in the left fronto-occipital fasciculus and the left inferior longitudinal fasciculus, which play important roles in processing of language and concept. Further, CRAT performance was negatively correlated with rWMV in the widespread frontal temporal subcortical and cerebellar WM areas, suggesting the unique association of convergent thinking with WM connectivity.

1. Introduction

Creativity is essential in the development of culture and society, and in laboratory settings, it is measured using tasks of divergent and convergent thinking. In divergent thinking tasks, participants are asked to generate as many answers as possible to a certain question. Conversely, in convergent thinking tasks, participants are asked to generate a single appropriate answer to a close-ended problem. A representative convergent thinking task for creativity is Remote Associates Test (RAT), which aims to evaluate individual ability to identify associations among remote ideas and has been widely used in the field (Li et al., 2019). One unique aspect of RAT is that when the problem is solved, an “Aha!” experience sometimes occurs (i.e., the solution comes to mind suddenly), which gives this task a characteristic of the insight task (Bowden and Jung-Beeman, 2003). In compound RAT (CRAT), participants are asked to see three hint words and produce a single solution word that can form compound words with these three hint words (e.g., hint words: pine, crab, and sauce; solution word: apple; compound words: pineapple, crabapple, and applesauce). It has been shown that associative fluency and associative flexibility show positive correlations...
with creative measures (Benedek et al., 2012). Further, RAT performance is reported to be positively correlated with other creativity measures, including the personality measure related to innovation and curiosity (Harris, 2004; Shen et al., 2016), anagram generation (Karp, 1966; Salvi et al., 2018), classic insight problems of multiple domains (Salvi et al., 2018), creative achievement measured by a questionnaire (Salvi et al., 2018), and fluency of divergent thinking (Salvi et al., 2018). However, it should also be noted that RAT performance is not only associated with measures related to creativity, but is also substantially positively correlated with basic cognitive functions such as psychometric intelligence, working memory capacity, and particularly crystalized intelligence or vocabulary (Ellis et al., 2019; Lee et al., 2014); insight problem solving is generally correlated with reasoning ability and working memory capacity (Chuderski and Jastrzębski, 2018).

Previous studies on convergent neuroscience have revealed that the findings of the rostral lateral prefrontal cortex, dorsolateral prefrontal cortex (DLPFC), and hippocampus are important for convergent creative thinking as described above. Stimulation of the left DLPFC results in an enhanced RAT performance (Zmigrod et al., 2015), whereas damage to the left rostral lateral prefrontal cortex and its connections results in an impaired RAT performance (Bendetowicz et al., 2017b). The meta-analyses of functional imaging studies on insight tasks, including the RAT, have revealed that the incubation phase of creative processes (attempts to solve problems and set induced restructuring) results in activation of the bilateral lateral prefrontal cortex and medial frontal cortex (Shen et al., 2018b). In addition, a lesion study has revealed that the lesions of the hippocampus cause deficits in RAT performance (Warren et al., 2016). Furthermore, the meta-analyses of functional imaging studies on insight tasks, including the RAT, have revealed that the phase of suddenly hitting upon the solution to the problem and the accompanying affective experience generates activity in the medial temporal lobes (Shen et al., 2018b).

Structural neuroimaging studies have investigated the anatomical correlates of convergent creative thinking performance (Bendetowicz et al., 2017a; Li et al., 2019; Ogawa et al., 2018). Bendetowicz et al. (2017a) have revealed that RAT performance is positively correlated with regional gray matter volume (rGMV) of the left rostral lateral prefrontal cortex and the left inferior parietal regions in the regions of interest analyses. However, these findings were not obtained in another study that reported different results using a lenient threshold (Ogawa et al., 2018). Li et al. (2019) used regional gray matter density (rGMD measure) and a statistical software called AlphaSim, which was shown to be anticonservative (Eklund et al., 2016), and found significant results in other areas, such as the right anterior temporal gyrus.

Despite several studies on convergent creative thinking and multiple reviews suggesting the importance of brain connectivity in creativity based on convergent evidence (Flaherty, 2005; Heilman et al., 2003), to the best of our knowledge, the following concerns remain unresolved: (a) No studies have investigated the associations between white matter (WM) structural properties measured using fractional anisotropy (FA) in diffusion tensor imaging (DTI) and individual convergent creative thinking performance, although one study has reported associations between graph theory-based connectivity measures and RAT performance using a small sample size (Wu et al., 2016). (b) No studies have investigated regional WM volume (rWMV) and individual convergent creative thinking performance. (c) In addition, as described above, the associations between RAT performance and rGMV have not been evaluated using robust statistics and previous findings were inconsistent.

In the present study, we aimed to address these unresolved concerns using CRAT, voxel by voxel structural connectivity analyses of FA in DTI (Le Bihan, 2003), rGMV, rWMV, and permutation-based statistics which were known to accurately control false positives as well as a large sample of young adults. In DTI, the FA in each voxel reflects several physiological components, including axonal membrane thickness, degree of myelination, and the diameter and amount of parallel organization of axons (Basser and Pierpaoli, 1996; Beaulieu, 2002), and can be used as a measure of WM strength. On the other hand, rWMV is weakly related to FA (Hugenschmidt et al., 2008) and appears to be sensitive to other WM characteristics (Fjell et al., 2008). Individual cognitive differences have reportedly demonstrated differential correlation patterns with rWMV and FA (Takeuchi et al., 2013b). Therefore, utilizing both measures can reveal the unique properties of WM correlates of individual cognitive differences. Using both these methods, we aimed to examine the long-standing viewpoint suggesting that brain connectivity is important in creativity.

Based on the abovementioned convergence of findings that suggest the importance of the rostro- and dorsolateral prefrontal cortex and hippocampus in creativity, we hypothesized that WM structural connectivity involving these areas are associated with convergent creative thinking. Further, similar to divergent thinking performance (Takeuchi et al., 2017b), convergent creative thinking performance may be associated with structural properties in widespread WM areas.

2. Methods

Participants. A total of 640 healthy, right-handed individuals (360 men and 280 women) participated in this study as part of our ongoing project to investigate the associations among brain imaging, cognitive function, and aging. Magnetic resonance imaging (MRI) and cognitive testing were performed on the same day in almost all the participants; however, at rare instances when this was not possible, MRI and cognitive testing were performed on separate days (with intervals from one to several days). The mean age of the participants was 20.9 years (standard deviation (SD), 1.6). All the participants were university, college, or postgraduate students or individuals who had graduated from these institutions within 1 year before the experiment. All the participants had normal vision, with no history of neurological or psychiatric illness. Handedness was evaluated using the Edinburgh Handedness Inventory (Oldfield, 1971). Written informed consent was obtained from each participant in accordance with the Declaration of Helsinki (1991). This study was approved by the Ethics Committee of Tohoku University. The descriptions in this subsection were mostly reproduced from our previous study using the exact same methods (Takeuchi et al., 2017b).

2.1. Japanese Remote Associates Test

The Japanese RAT (JRAT) was used to evaluate convergent creative thinking performance. The RAT is a widely used measure of convergent creative thinking (Mednick, 1962), and the JRAT is one of the measures of the CRAT. The JRAT was developed for Japanese participants (Terai et al., 2013).

In the JRAT, each item comprises three Japanese words formed with two Japanese kanji [e.g., 共存 (kyou-zon, coexistence), 悲願 (hi-gan, ardent wish), and 雷雨 (rai-u, thundery rain)]. Participants are asked to replace the second kanji with one kanji that can form three proper words with the first kanji of three presented Japanese words [e.g., 嘯鳴 (kyou-mei, resonance), 悲鳴 (hi-mei, scream), and 雷鳴 (rai-mei, thunderclap)]. There are two versions of this test. One version presents three meaningful Japanese words with two kanji letters (the example presented above is one item of this version) and the second version presents three meaningless Japanese words with two kanji letters. We used the former version because it has been shown to be more difficult (Terai et al., 2013). Each version has 79 items, but we split the 79 items into two (39 and 40 items) and used only 39 items. All the participants were asked to solve the same 39 items; they were asked to solve as many of these items as possible in 15 min using papers and pencils.

Our unpublished intervention study revealed that after an interval of approximately 1 year, the split half test–retest reliability (the correlation between the score on version 1 at time point 0 and the score on version 2 1 year later) was 0.527 among 42 young adults assigned to the non-intervention group, suggesting the reliability of the JRAT. Further, in the present study (Table 2), JRAT performance was shown to be
positively correlated with non-verbal reasoning test (Raven’s Advanced Progressive Matrix [RAPM]) \((r = 0.181)\) and divergent thinking test performance (S-A creativity test) \((r = 0.143)\), which is consistent with a previous study (Lee et al., 2014). Taken together, these results support the validity of the JRAT.

### 2.2. Assessment of the psychometric measures of general intelligence

We used RAPM to evaluate participants’ intelligence and to adjust the effect of general intelligence on brain structures. RAPM is often shown to be most correlated with general intelligence and has been used as a measure of general intelligence (Raven, 1998). RAPM was also adjusted in the whole brain multiple regression analyses to rule out the possibility that any correlations between JRAT performance and brain structures were not caused by the correlation between general intelligence and brain structures (Jung and Haier, 2007), or the correlation between general intelligence and JRAT performance. The details of the administration of RAPM are provided in the Supplemental Methods.

### 2.3. Other psychological measures

We also used the psychological measures described below. We used RAPM and these other measures to show that the psychometric property of JRAT performance is similar to that of performance of RAT measures used in previous studies. The descriptions in this subsection were mostly reproduced from our previous studies using the same measures in the same way (Takeuchi et al., 2015, 2019).

- **(A) S-A creativity test.** Creativity measured by divergent thinking was evaluated using the S-A creativity test (Society For Creative Minds, 1969). The details of this test are provided in the Supplemental Methods.
- **(B) Perception factor of the Tanaka B-type intelligence test (TBIT) (Tanaka et al., 2003) type 3B.** This is a mass intelligence test used for 3rd-year junior high school and older participants. The perception speed factor of TBIT measures simple processing speed. In all the subtests, participants must solve as many problems as possible in a certain time (a few minutes). Additional details of this test are provided in the Supplemental Methods.

### Image acquisition.

The descriptions in this subsection were mostly reproduced from our previous study using the same methods (Takeuchi et al., 2017b). All MRI data acquisition was performed using a 3-T Philips Achieva scanner. High-resolution T1-weighted structural images (T1WIs: \(240 \times 240\) matrix, TR = 6.5 ms, TE = 3 ms, FOV = 24 cm, slices = 162, slice thickness = 1.0 mm) were collected using a magnetization-prepared rapid gradient echo sequence.

Diffusion-weighted data were acquired using a spin-echo EPI sequence (TR = 10293 ms, TE = 55 ms, big delta (\(\Delta\)) = 26.3 ms, little delta (\(\delta\)) = 12.2 ms, FOV = 22.4 cm, \(2 \times 2 \times 2 \text{ mm}^3\) voxels, 60 slices, SENSE reduction factor = 2, number of acquisitions = 1). The diffusion weighting was isotropically distributed along 32 directions (b value = 1000 s/mm\(^2\)). Additionally, three images with no diffusion weighting (b = 0 s/mm\(^2\)) were acquired using a spin-echo EPI sequence (TR = 10293 ms, TE = 55 ms, FOV = 22.4 cm, \(2 \times 2 \times 2 \text{ mm}^3\) voxels, 60 slices). From the acquired images, FA and mean diffusivity (MD) maps were generated using the commercially-available diffusion tensor analysis package on the MR console. These processes involved correction for motion and distortion caused by eddy currents using methods described previously (Netsch and Van Muijswinkel, 2004). Calculations were performed according to a previously proposed method (Le Bihan et al., 2001). MD maps were irrelevant to the purpose of this study but were used in a preprocessing step as described previously (Takeuchi et al., 2013b). The descriptions in this subsection were mostly reproduced from our previous study using the same methods (Takeuchi et al., 2017b).

### Preprocessing of structural data.

Preprocessing of structural data was performed using Statistical Parametric Mapping (SPM) software (SPM12; Wellcome Department of Cognitive Neurology, London, UK) implemented in MATLAB (Mathworks Inc., Natick, MA, USA). Using the new segmentation algorithm implemented in SPM12, T1-weighted structural images of each participant were segmented into six tissues. Note that SPM12 was used for voxel-based morphometry (VBM) because of its better quality of preprocessing, whereas SPM8 was used elsewhere in this study because of its compatibility with the software of the version we used (for statistical tests) or for better preprocessing quality for DTI.

The default parameters were used in the new segmentation process, except that the Thorough Clean option was used to eliminate any odd voxels. Affine regularization was performed with the International Consortium for Brain Mapping template for East Asian brains, with the sampling distance set at 1 mm. We then proceeded to diffeomorphic anatomical registration through the exponentiated lie algebra (DARTEL) registration process implemented in SPM12. We used DARTEL import images of the two TPMs from the abovementioned new segmentation process. First, a template for the DARTEL procedures was developed using imaging data from 800 participants (400 males and 400 females). Subsequently, the DARTEL procedures were performed using this template in all the participants in the study using the default parameter settings. The resulting images were spatially normalized to Montreal Neurological Institute (MNI) space to produce images with voxels of \(1.5 \times 1.5 \times 1.5 \text{ mm}^3\). In addition, we performed a volume change correction (modulation) by modulating each voxel with the Jacobian determinants derived from spatial normalization, which allowed us to determine regional differences in the absolute amount of brain tissues (Ashburner and Friston, 2000). Subsequently, all images were smoothed by convolving them with an isotropic Gaussian kernel of 8 mm full width at half maximum (FWHM).

Preprocessing of diffusion data was performed using SPM8 software (SPM8; Wellcome Department of Cognitive Neurology, London, UK) implemented in MATLAB (Mathworks Inc., Natick, MA, USA). Using the previously validated twisted methods (Takeuchi et al., 2013b), new segmentation algorithm implemented in SPM8, and FA and MD image information, we segmented the FA and MD images for all participants (refer our previous study (Takeuchi et al., 2013b) for details and validation). Next, we mainly normalized FA, gray matter segments (regional gray matter density [rGMD] map), WM segments (regional white matter density [rWMD] map), and cerebrospinal fluid (CSF) segments (regional CSF density [rCSFD] map) of the diffusion images of the participants with previously validated DARTEL-based registration process method modified to account for the signal distribution of FA within WM to acquire images with a \(1.5 \times 1.5 \times 1.5 \text{ mm}^3\) voxel size. Next, the normalized FA images were masked using the custom mask image, which is highly likely to be WM, and smoothed with a Gaussian kernel of 6 mm FWHM. The details of these preprocessing procedures and their validation are presented in our previous study (Takeuchi et al., 2013a). Briefly, by accounting for FA signal variability within the WM areas in the DARTEL procedures, misalignment of the tracts was prevented. Further, by applying stringent masking of the WM areas, signal contamination from other tissues was prevented. Our method effectively solved or alleviated the major problems of voxel-based analyses of FA images (Smith et al., 2006). The descriptions in this subsection were mostly reproduced from our previous study using the same methods (Takeuchi et al., 2017b). Additional details of the preprocessing procedures for FA maps are provided in the Supplemental Methods.

### Table 1

| Participant characteristics and test scores (mean, standard deviation [SD], and range) |
|-----------------------------------|-----------------|-----------------|
|                                    | average         | SD              | range           |
| JRAT score                         | 18.28           | 4.68            | 2–32            |
| RAPM score                         | 28.50           | 4.04            | 8–36            |
| Age (years)                        | 20.93           | 1.61            | 18–27           |
2.4. Statistical analysis of psychological data

In the analyses of psychological data, results with a threshold of $P < 0.05$, corrected for false discovery rate (FDR) using the classical one stage method (Benjamini and Hochberg, 1995) were considered statistically significant. Correction for multiple comparisons using this method was applied to the results of the six multiple regression analyses listed in Table 2.

2.5. Whole-brain statistical analysis

Using VBM, we investigated if rGMV, rWMV, and FA were associated with individual differences in JRAT scores. Statistical analyses of imaging data were performed using SPM8. We performed whole-brain multiple regression analyses with sex, age, TIV, and RAPM scores as covariates. In the analyses of rGMV and rWMV, we included only voxels that showed a signal intensity greater than 0.05 in all participants. The analyses of FA were limited to the WM mask developed above.

Correction for multiple comparisons was performed using threshold-free cluster enhancement (TFCE) (Smith and Nichols, 2009) with randomized (5000 permutations) nonparametric testing using the TFCE toolbox (http://dbm.neuro.uni-jena.de/tfce/). We applied a threshold of $P < 0.05$ with corrections for family-wise error (FWE). The descriptions in this subsection were mostly reproduced from our previous study (Takeuchi et al., 2018).

In this study, we corrected the effects of psychometric measures of intelligence (RAPM scores) in the whole brain multiple regression analyses. However, these score were significantly positively correlated with JRAT scores, as described above. Thus, we also conducted analyses without RAPM scores as a covariate. The results are presented in Supplemental Fig. 1. The significant areas got wider when the RAPM score were not included as covariates in rWMV and FA analyses. In addition, in FA analyses without RAPM score as a covariate, the significant areas were also seen in the contingent areas and in the contralateral homolog of the significant area in the analysis with RAPM score as a covariate. Overall, the conclusions and discussions in the main text were not altered by these changes.

3. Results

3.1. Basic behavioral data

The average, SD, and range of JRAT scores, RAPM scores, and participant age are presented in Table 1. The distribution of JRAT scores was presented in Fig. 1. After correcting for confounding variables and multiple comparisons, the multiple regression analysis revealed that JRAT score was significantly positively correlated with S-A creativity test score (divergent thinking performance), RAPM score (fluid intelligence measured by non-verbal reasoning), and the perception factor of the TBIT (simple processing speed). Full statistical results are presented in Table 2.

Table 2
Statistical values of multiple regression analyses between psychological variables and JRAT scores after correction for confounding variables, as well as simple correlation coefficients between them.

| Dependent variable | N | Multiple regression | Simple correlation |
|--------------------|---|---------------------|--------------------|
|                    |   | $\beta$ | $t$ | $P$ (uncorrected) | $P$ (FDR) | $r$ |
| RAPM$^b$ | 640 | 0.189 | 4.866 | 1.44$\times 10^{-6}$ | 2.16$\times 10^{-6}$ | 0.181 |
| S-A creativity test | 640 | 0.139 | 3.537 | 4.33$\times 10^{-4}$ | 4.33$\times 10^{-4}$ | 0.143 |
| TBIT$^c$-Perception speed factor | 640 | 0.299 | 7.934 | 9.62$\times 10^{-15}$ | 2.87$\times 10^{-14}$ | 0.302 |

$^a$False discovery rate. $^b$Raven’s advanced progressive matrices (a general intelligence task).

Fig. 1. Distribution of JRAT scores in the study sample.

Fig. 2. Associations between convergent creative thinking performance and rWMV. (a) The panels show the areas of significant negative correlation between JRAT score and rWMV. The results shown were obtained using a threshold of TFCE, $P < 0.05$ corrected (FWE) based on 5000 permutations. The color represents the strength of TFCE values. Regions of correlation are overlaid on a single subject T1 image in SPM. Significant correlations were found across the widespread white matter areas. (b) Scatterplot of the association between JRAT score and mean rWMV values of the largest cluster.
and rWMV.

Table 3

| Included large bundles** (number of significant voxels in the left and right side of each anatomical area) | x   | y   | z   | TFCE value | Corrected P value (TFCE, FWE) | Cluster size (voxel) |
|--------------------------------------------------------|-----|-----|-----|------------|-------------------------------|---------------------|
| Middle cerebellar peduncle (5182)/Ponitine crossing tract (522)/ | 27  | −53 | −34.5 | 2126.13 | 0.003                         | 41527               |
| Genu of corpus callosum (2539)/Body of corpus callosum (1509)/ | | | | | | |
| Splenium of corpus callosum (7)/ | | | | | | |
| Medial lemniscus (L:255, R:252)/ | | | | | | |
| Inferior cerebellar peduncle (L:223, R:137)/ | | | | | | |
| Superior cerebellar peduncle (L:332, R:201)/ | | | | | | |
| Corticospinal tract (L:431, R:441)/ | | | | | | |
| Anterior limb of internal capsule (L:222, R:633)/ | | | | | | |
| Posterior limb of internal capsule (L:261, R:228)/ | | | | | | |
| Retrolenticular part of internal capsule (L:113)/ | | | | | | |
| Anserior corona radiata (L:760, R:999)/ | | | | | | |
| Superior corona radiata (R:584)/ | | | | | | |
| Posterior thalamic radiation (L:338)/ | | | | | | |
| Sagittal stratum (L:386)/ | | | | | | |
| External capsule (L:182, R:270)/ | | | | | | |
| Cingulum (L:96, R:593)/Stria terminalis (L:143)/ | | | | | | |
| Superior longitudinal fasciculus (L:105)/ | | | | | | |
| Superior fronto-occipital fasciculus (R:155)/ | | | | | | |
| Inferior fronto-occipital fasciculus (L:186, R:210)/ | | | | | | |
| 36 | −34.5 | 40.5 | 1162.23 | 0.031 | 565 |

* The anatomical labels and significant clusters of major white matter fibers were determined using the ICBM DTI-81 Atlas (http://www.loni.ucla.edu/).

3.2. Associations between JRAT score and rGMV/rWMV

Whole-brain multiple regression analysis of rGMV revealed that, after correcting for confounding variables, JRAT score did not show any significant correlations.

The whole-brain multiple regression analysis revealed that after correcting for confounding variables, the JRAT score was significantly and negatively correlated with rWMV in extensive WM areas. These areas included the cerebellum, brain stem, bilateral internal capsule, external capsule, corticospinal tract, corpus callosum (mainly the genu and body area), bilateral inferior fron-to-occipital fasciculus (FOF), bilateral anterior corona radiata, right superior corona radiata, left posterior thalamic radiation, left sagittal stratum, left stria terminalis, left superior longitudinal fasciculus, right superior FOF, and right superior longitudinal fasciculus (Fig. 2, Table 3). The mean rWMV of areas of significant negative correlation between the JRAT score and rWMV did not show significant correlation with RAPM score in the simple regression analysis or in the multiple regression analysis correcting for age and sex (p > 0.1).

3.3. Associations between JRAT score and FA

The whole-brain multiple regression analysis revealed that, after correcting for confounding variables, JRAT score was significantly and positively correlated with FA in the WM area of the left inferior longitudinal fasciculus and left FOF (Fig. 3, MNI coordinates: x, y, z = −36, −52.5, −1.5, peak TFCE value = 520.81, p = 0.018 FWE-corrected [permutation, TFCE], 77 voxels). This area was included in the areas showing significant negative correlation between JRAT score and rWMV.

The mean FA of areas of significant negative correlation between the JRAT score and FA did not show significant correlation with RAPM score in the simple regression analysis or in the multiple regression analysis correcting for age and sex (p > 0.1).

4. Discussion

This study investigated the associations between individual CRAT performance, which is a measure of convergent creative thinking, and rGMV, rWMV, and FA in a large sample using robust permutation-based statistical techniques. Under this condition, we failed to find significant rGMV correlates of CRAT performance, similar to that in our previous investigation on rGMV correlates of divergent thinking performance (Takeuchi et al., 2017b). For rWMV, consistent with one of our hypotheses, CRAT performance was correlated with rWMV in widespread WM areas, including those close to the lateral prefrontal cortex and anterior part of the corpus callosum, which connects the bilateral lateral prefrontal cortex, which was also consistent with our hypothesis. However, in contrast with our hypothesis, CRAT performance was negatively (rather than positively) correlated with rWMV. Finally, CRAT performance was positively correlated with FA in the WM bundle of the left inferior longitudinal fasciculus and the left FOF. This finding may be
partly in line with our hypothesis, given that the FOF connects the lateral and other parts of the prefrontal cortex with the occipital areas described below.

WM in the left temporal areas, where FA was positively correlated with CRAT performance, included the left FOF and left ILF, which play important roles in language and concept. The FOF connects the frontal lobe (orbitofrontal cortex and other lateral prefrontal regions) with the posterolateral temporal and occipital lobes (Schmahmann and Pandya, 2007). This tract comprises the “semantic ventral stream,” which is crucial for language semantic processing, and elicits semantic paraphasia when stimulated (Mandonnet et al., 2007). The lateral prefrontal regions include areas that are shown to be important for RAT performance or language processing. As described in the Introduction, RAT performance is compromised by the lesion of the RLPC, which is involved in certain types of integration of multiple types of information (Bendetowicz et al., 2017b). The meta-analysis shows that areas involving the RLPC, DLPC, and ventrolateral prefrontal cortex are more activated during the tasks than tasks involving free generation of ideas (Gonen-Yaacovi et al., 2013). The DLPC was shown to be important in RAT performance in transcranial direct current stimulation (tCDS) studies (Zmigrod et al., 2015). Review articles suggest this area has a number of important functions that may be relevant to certain aspects of creativity, such as attention, cognitive control, flexible problem solving, working memory, semantic retrieval, episodic encoding and retrieval, priming, and explicit categorization (Flaherty, 2005; Haier and Jung, 2008). The ventrolateral prefrontal cortex has a number of important functions that may be relevant to certain aspects of creativity, the generation of verbal information, and connect posterior brain areas and frontal and temporal areas.

Areas with significant correlation between rWMV and CRAT performance included several WM areas relevant to integration of information, transfer of information, and language and conceptual processing. Besides the areas described for the results of FA (ILF, FOF, lateral frontal areas, anterior temporal lobe, and fusiform gyrus), areas of significant correlation of rWMV were widespread and included the following: the body and genu of the corpus callosum, which connects the bilateral prefrontal regions (De Lacoste et al., 1985); motor, sensory, and auditory cortices (Pandya et al., 1986), which are involved in interhemispheric information processing (Schulte et al., 2005); WM areas close to the basal ganglia architectures, which are involved in cognitive flexibility through the fronto-striatal circuits through dopaminergic functions (Middleton and Strick, 2002; Monchi et al., 2001); WM areas close to the hippocampus, which are involved in memory processing and lesions to which alter RAT performance (Warren et al., 2016); WM areas close to the cerebellum have a wide range of functions associated with creative processes, such as the articulatory loop function of working memory, language, learning and mental models (Takeuchi et al., 2017a; Vandervert et al., 2007); and WM areas close to the temporo-parietal junction, which is involved in integration of multisensory information (Spence and Frith, 1999), while the information integration of information of different modalities is suggested to be important for creativity through the combination of different types of information (Spearman, 1931). However, it should be noted that these are unavoidable reverse inferences, and other functions of the areas may be more relevant. Associations with widespread brain areas may be consistent with the view that during a wide range of creative processes, dynamic interactions of large-scale brain systems, particularly those of the default mode network and executive control network, tend to cooperate (for review, see Beatty et al., 2016).

However, it is interesting the CRAT performance was negatively (rather than positively) correlated with rWMV. Moreover, CRAT performance was positively correlated with FA and negatively correlated with rWMV in overlapping areas. The mechanisms of these findings were not clear. However, rWMV and FA are both thought to be associated with WM property, but they are only weakly associated in deep WM areas (Hugenschmidt et al., 2008) and are assumed to reflect different physiological components or properties of WM. For example, WM fibers running in one direction in an organized manner can result in a higher FA without affecting rWMV. Other physiological properties, such as the presence of fewer axon collateral spines, result in a lower rWMV but unchanged FA. However, the present study cannot reveal these underlying mechanisms, and these unexpected findings remain to be replicated.

The reasons and physiological background underlying the observed negative correlation between rWMV and CRAT performance are unclear, and we can only speculate the underlying reasons. A negative correlation between CRAT performance and rWMV was observed despite the fact that divergent thinking performance is positively correlated with widespread WM areas in females (Takeuchi et al., 2017b). In the present study, divergent thinking performance (S-A creativity test score) was positively correlated with CRAT performance. However, it is previously
known that convergent creative and divergent thinking performance have certain opposing characteristics. For example, it is suggested that divergent thinking performance has an inverted U-shaped relationship with dopamine levels, whereas convergent thinking tends to be negatively correlated with dopamine levels (Chermahini and Hommel, 2010). On the other hand, risk-taking tendency showed a positive correlation with divergent thinking performance (Eisenman, 1987) but a negative correlation with convergent creative thinking performance (Shen et al., 2018a). Other review article suggests the dual pathway to creativity model (Boot et al., 2017). According to this model, creative outputs result from two cognitive processes—flexibility and persistence. The flexibility pathway involves broad attentional scope, divergent thinking, flexible switching between perspectives, and so on, while the persistence pathway includes more convergent, focused thinking and incremental search processes and so on. The former is assumed to be subserved by the striatum and its dopamine system, while the latter is assumed to be subserved by the prefrontal cortex and its dopaminergic system (Boot et al., 2017). In addition, there is not only interplay between the two systems, but it has also been suggested that there is a certain trade-off between the two systems (Boot et al., 2017). The exact physiological mechanisms leading to the positive correlations between rWMV and divergent thinking performance, and the negative correlations between rWMV and convergent creative thinking performance, are not clear, and we do not speculate on such mechanisms in this study. But the present study extends a series of opposing characteristics of divergent thinking and convergent thinking.

In conclusion, this study investigated the associations between CRAT performance and rGMV in young adults. As described in the Introduction section, three previous studies that investigated the associations between regional gray matter structures and convergent creative thinking performance using a lenient threshold, an anticonservative statistical method, and a region of interest—findings (Bendetowicz et al., 2017a; Li et al., 2019; Ogawa et al., 2018). To the best of our knowledge, the present study used the largest sample to date to investigate the associations between convergent creative thinking performance and rGMV. Alternatively, lower brain connectivity may be related to better convergent thinking performance because the eliminated synapses may prohibit irrelevant information processing and allow participants to promote correct ideas. However, these are speculations and future studies are warranted to confirm these possibilities. On the other hand, Failure to find significant correlation between CRAT performance and rGMV may be a result of the complex nature of rGMV in young adults. As described in the Introduction section, three previous studies that investigated the associations between regional gray matter structures and convergent creative thinking performance using a lenient threshold, an anticonservative statistical method, and a region of interest—approach have reported divergent findings (Bendetowicz et al., 2017a; Li et al., 2019; Ogawa et al., 2018). To the best of our knowledge, the present study used the largest sample to date to investigate the associations between convergent creative thinking performance and regional gray matter structures using permutation-based robust statistics. However, the lack of significant associations—despite the use of a large young adult normal sample, established performance-based cognitive measure, and robust permutation-based statistics—is common to our previous study on the associations between rGMV and divergent thinking performance in 1336 young adults (Takeuchi et al., 2017b). Together these results suggest that cognitive measures do not always have robust rGMV correlates in these settings. Investigations of the associations between regional gray matter structures and divergent thinking performance may be negatively affected by low replicability (Takeuchi and Kawashima, 2017). We attributed this phenomenon to several factors, including the complex ambivalent nature of regional gray matter structures, for which a lower amount is associated with advanced development as well as regional gray matter atrophy. Moreover, these factors include the complex ambivalent psychological nature of divergent thinking, which is known to increase dopamine receptor density (Jönsson et al., 1999), is reportedly associated with a lower rWMV in widespread thalamocortical and limbic WM areas (Nagase et al., submitted). It is possible that physiological mechanisms relevant to these properties mediate the negative correlation between convergent creative thinking performance and rWMV. Alternatively, lower brain connectivity may involve broader attentional scope, flexible switching between perspectives, and so on, while the persistence pathway includes more convergent, focused thinking and incremental search processes and so on. The former is assumed to be subserved by the striatum and its dopamine system, while the latter is assumed to be subserved by the prefrontal cortex and its dopaminergic system (Boot et al., 2017). The exact physiological mechanisms leading to the positive correlations between rWMV and divergent thinking performance, and the negative correlations between rWMV and convergent creative thinking performance, are not clear, and we do not speculate on such mechanisms in this study. But the present study extends a series of opposing characteristics of divergent thinking and convergent thinking.

In conclusion, this study investigated the associations between CRAT performance and brain structures using a large sample size and robust permutation-based statistics. We failed to find significant associations between rGMV and CRAT performance. However, we showed that CRAT performance was positively correlated with a WM pathway property (i.e., FA) in the left FOF and left ILF, which play important roles in language and concepts. Furthermore, CRAT performance was negatively correlated with rWMV in the widespread frontal, temporal, subcortical, and cerebellar WM areas, suggesting the unique association of convergent thinking with WM connectivity compared with divergent thinking.

Acknowledgments

We thank Kento Takahashi for operating the MRI scanner, all other assistants for helping with the experiments and the study, and the study participants, and all our other colleagues at IDAC, Tohoku University for their support. This study was supported by JST/RISTEX, JST/CREST, and a Grant-in-Aid for Young Scientists (A) (KAKENHI 25700012) from the Ministry of Education, Culture, Sports, Science, and Technology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116577.

References

Ashburner, J., Friston, K.J., 2000. Voxel-based morphometry-the methods. Neuroimage 11, 805–821.

Basser, P.J., Pierpaoli, C., 1996. Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. J. Magn. Reson., Ser. B 111, 209–219.

Beaty, R.E., Benedek, M., Kaufman, S.B., Silvia, P.J., 2015. Default and executive network coupling supports creative idea production. Sci. Rep. 5.

Beaty, R.E., Benedek, M., Silvia, P.J., Schacter, D.L., 2016. Creative cognition and brain network dynamics. Trends Cognit. Sci. 20, 87–95.

Beaulieu, C., 2002. The basis of anisotropic water diffusion in the nervous system—a model (Boot et al., 2017). According to this model, creative outputs result from two cognitive processes—flexibility and persistence. The flexibility pathway involves broad attentional scope, divergent thinking, flexible switching between perspectives, and so on, while the persistence pathway includes more convergent, focused thinking and incremental search processes and so on. The former is assumed to be subserved by the striatum and its dopamine system, while the latter is assumed to be subserved by the prefrontal cortex and its dopaminergic system (Boot et al., 2017). The exact physiological mechanisms leading to the positive correlations between rWMV and divergent thinking performance, and the negative correlations between rWMV and convergent creative thinking performance, are not clear, and we do not speculate on such mechanisms in this study. But the present study extends a series of opposing characteristics of divergent thinking and convergent thinking.

In conclusion, this study investigated the associations between CRAT performance and brain structures using a large sample size and robust permutation-based statistics. We failed to find significant associations between rGMV and CRAT performance. However, we showed that CRAT performance was positively correlated with a WM pathway property (i.e., FA) in the left FOF and left ILF, which play important roles in language and concepts. Furthermore, CRAT performance was negatively correlated with rWMV in the widespread frontal, temporal, subcortical, and cerebellar WM areas, suggesting the unique association of convergent thinking with WM connectivity compared with divergent thinking.

Acknowledgments

We thank Kento Takahashi for operating the MRI scanner, all other assistants for helping with the experiments and the study, and the study participants, and all our other colleagues at IDAC, Tohoku University for their support. This study was supported by JST/RISTEX, JST/CREST, and a Grant-in-Aid for Young Scientists (A) (KAKENHI 25700012) from the Ministry of Education, Culture, Sports, Science, and Technology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116577.

References

Ashburner, J., Friston, K.J., 2000. Voxel-based morphometry—the methods. Neuroimage 11, 805–821.

Basser, P.J., Pierpaoli, C., 1996. Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. J. Magn. Reson., Ser. B 111, 209–219.

Beaty, R.E., Benedek, M., Kaufman, S.B., Silvia, P.J., 2015. Default and executive network coupling supports creative idea production. Sci. Rep. 5.

Beaty, R.E., Benedek, M., Silvia, P.J., Schacter, D.L., 2016. Creative cognition and brain network dynamics. Trends Cognit. Sci. 20, 87–95.

Beaulieu, C., 2002. The basis of anisotropic water diffusion in the nervous system—a technical review. NMR Biomed. 15, 435–455.
Araki, T., Hashizume, H., Sassa, Y., Kawashima, R., 2015. Brain structures in the sciences and humanities. Brain Struct. Funct. 220, 3295–3305.

Takeuchi, H., Taki, Y., Thyreau, B., Sassa, Y., Hashizume, H., Sekiguchi, A., Nagase, T., Nouchi, R., Fukushima, A., Kawashima, R., 2013b. White matter structures associated with empathizing and systemizing in young adults. Neuroimage 77, 222–236.

Terai, H., Miwa, K., Asami, K., 2013. Development and evaluation of the Japanese remote Associates test. Jpn. J. Psychol. 84, 419–428.

Vandervort, L.R., Schimpf, P.H., Liu, H., 2007. How working memory and the cerebellum collaborate to produce creativity and innovation. Creativ. Res. J. 19, 1–18.

Warren, D.E., Kurczek, J., Duff, M.C., 2016. What relates newspaper, definite, and clothing? An article describing deficits in convergent problem solving and creativity following hippocampal damage. Hippocampus 26, 835–840.

Wu, C., Zhong, S., Chen, H., 2016. Discriminating the difference between remote and close association with relation to white-matter structural connectivity. PloS One 11, e0165053.

Zmigrod, S., Colzato, L.S., Hommel, B., 2015. Stimulating creativity: modulation of convergent and divergent thinking by transcranial direct current stimulation (tDCS). Creativ. Res. J. 27, 353–366.

World Medical Association, 1991. Declaration of Helsinki. Law, Medicine & Health Care 19, 264. A Publication of the American Society of Law & Medicine.