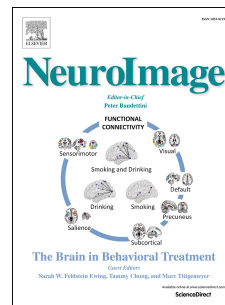


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Originality of divergent thinking is associated with working memory–related brain activity: evidence from a large sample study

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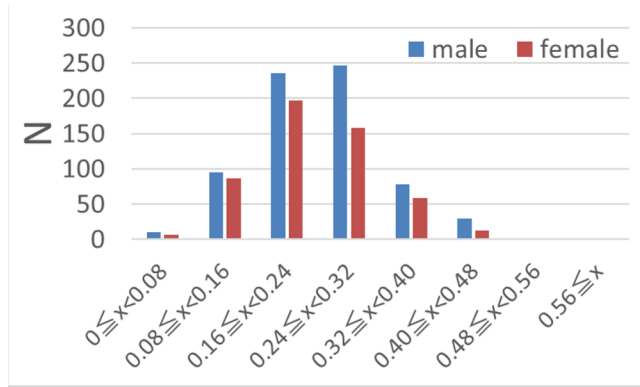
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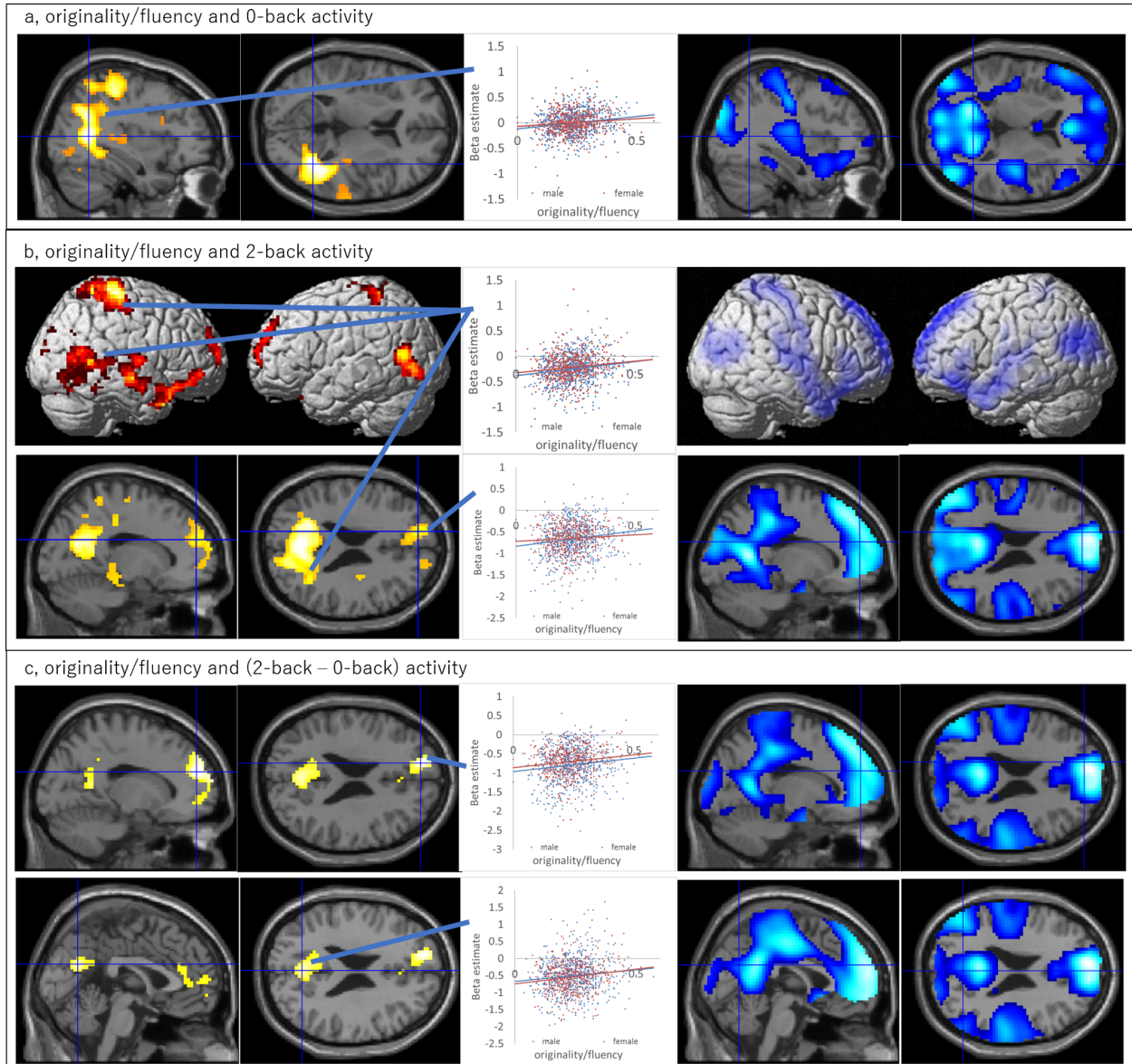
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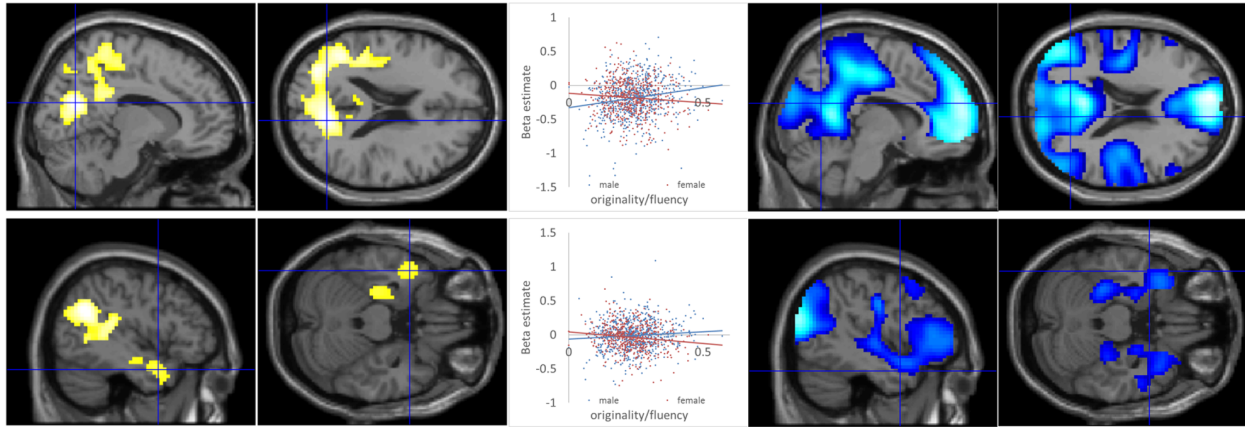
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Journal Pre-proof



originality/fluency and 0-back activity



Originality of divergent thinking is associated with working memory–related brain activity: evidence from a large sample study

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Abstract

The originality of creativity measured by divergent thinking (CMTD) is a unique variable that is positively correlated with psychometric intelligence and other psychological measures. Here, we aimed to determine the associations of CMTD originality/fluency scores and brain activity associated with working memory (WM) and simple cognitive processes during the N-back paradigm in a cohort of 1221 young adults. We observed that originality/fluency scores were associated with greater brain activity during the 0-back simple cognitive task and 2-back WM task in key nodes of the ventral attention system in the right hemisphere. Further, subjects with higher originality/fluency scores showed lower task-induced deactivations in areas of the default mode network, especially during the 2-back task. Psychological analyses revealed the associations of originality/fluency scores with both psychometric intelligence and systemizing. We also observed the effects of interaction between sex and originality/fluency scores on functional activity during the 0-back task in posterior parts of the default mode network together with other areas as well as simple processing speed. These results indicate that the originality of CMTD is associated with (a) greater activation of the ventral attention system, which is involved in reorienting attention and (b) reduced task-induced deactivation of the default mode network, which is indicative of alterations in attentional reallocation, and (c) cognitive correlates of originality of CMTD and revealed sex differences in these associations.

Introduction

Creativity has been essential for the development of human civilization. In laboratory settings, creativity is commonly measured by divergent thinking tests (creativity measured by divergent thinking [CMTD]). Divergent thinking involves information retrieval and call for a number of responses to a certain question (Guilford, 1967). A meta-analysis demonstrated that performance on divergent thinking tests predicts creative achievement in real-life settings well, suggesting the validity of divergent thinking tests (for the meta analysis, see Kim, 2008). However, the effect size of the relationship between divergent thinking performance and “real-life” creative achievement tends to be weak in general (for review, see Kim, 2006).

One interesting characteristic of individuals with greater creativity is that they often exhibit unique associations of CMTD with attentional processes. Some of these associations are common to subjects with low working memory capacity (WMC), although there are no studies, to the best of our knowledge, showing a negative correlation between creativity and WMC. For example, individuals with greater creativity demonstrated greater difficulty with selective attention tasks (Necka, 1999), and subjects with higher creativity for poetry were worse at ignoring irrelevant stimuli (Kasof, 1997), which is also common in subjects with low WMC (Conway et al., 2001). Further, studies using a dichotic listening paradigm, in which subjects must attend to information presented to one ear and ignore the information presented to the other ear, have also reported subjects with greater creativity are worse at ignoring the stimuli from the unattended ear, which is also the characteristic of subjects with lower WMC (Dykes and McGhie, 1976; Rawlings, 1985). Numerous other psychological metrics have revealed an association between the breadth of attention and greater creativity

(Friedman et al., 2003). In addition, some clinical studies have found that attention deficit and/or hyperactivity are also associated with both lower WMC and greater creativity (Kuntsi et al., 2001; Shaw, 1992; White and Shah, 2006). In addition, reducing attention deficit/hyperactivity using Ritalin also reduced creativity, while improving WMC (Mehta et al., 2004; Swartwood et al., 2003). Yet other studies have reported that creative subjects show slower responses in ill-defined tasks or tasks requiring inhibition of irrelevant information, but faster responses in tasks without such requirements and on the basis of these findings, it is suggested creative subjects may be able to focus or defocus attention more efficiently depending on task demands (Benedek et al., 2012; Vartanian, 2009). . Interventional studies have also reported that training paradigms aimed at broadening attention can improve creative performance (Memmert, 2007; Takeuchi et al., 2014a). In addition, our intervention study revealed that WM training using the mental calculation paradigm, which requires prolong focus of attention, can reduce creative performance (Takeuchi et al., 2011d). Moreover, genetic studies have found associations between a polymorphism of the neuregulin 1 gene and the risk of psychosis (Kéri et al., 2009), which is traditionally believed to be associated with selective attention deficit and dysfunction of attentional filtering (Garmezzy, 1977). In addition, the polymorphism of neuregulin 1 gene is reportedly associated with lower WMC (Stefanis et al., 2007) and greater creativity (Kéri, 2009).

On the other hand, it has been shown that subscores on divergent thinking tests—such as fluency, flexibility, originality, and elaboration—are highly correlated with one another when scoring is performed using the traditional method (Torrance, 1966); therefore, separate interpretation of subscores may be challenging (Treffinger, 1985). However, recent studies have shown specificities or independent contributions of

originality relative to other subscores, especially fluency (Jauk et al., 2014), and these findings focused on psychometric intelligence and certain attention-related psychological characteristics. For example, it has also been shown that the minimum level of creativity necessary for high level originality is greater than that for fluency (Jauk et al., 2014). Psychologically, psychometric intelligence is correlated more strongly with originality than with fluency of divergent thinking (Jauk et al., 2013), and ability associated with updating—as well as that of retrieval—are both associated with intelligence and originality (Benedek et al., 2014; Benedek et al., 2017). By contrast, performance of inhibition tasks is more closely associated with fluency than with originality (Benedek et al., 2012). Further, limited evidences suggested the possible involvement of attentional processes in this association. For example, a previous study found that the percentage of unique words and associations generated in poems were positively associated with a wider breadth of attention (lower stimulus screening) (Kasof, 1997). Findings in subjects with attention deficit and/or hyperactivity are divided, but White and Shah (2011) reported that subjects with attention deficit hyperactive disorder (ADHD) show greater originality, but not fluency. Priming for broader attention also led to the generation of original responses when subjects were asked to generate only single answers (Friedman et al., 2003). Subjects with the risk polymorphism for ADHD also demonstrated greater originality but not fluency (Takeuchi et al., 2015d).

Neuroscience research also supports distinctions between originality and other subscores of divergent thinking, particularly fluency, as well as common neural correlates. For example, inhibition of the left prefrontal cortex and excitation of the right prefrontal cortex (particularly the inferior frontal gyrus) improved fluency and

flexibility, but not originality, during a divergent thinking task (Chrysikou et al., 2013). Lesions involving the medial prefrontal cortex, right inferior frontal gyrus, or temporoparietal areas reduce originality, whereas lesions involving left temporoparietal areas and possibly the left IFG lead to increased originality (Shamay-Tsoory et al., 2011). Lesions of the lateral PFC and frontotemporal dementia lead to the reduction in fluency as well as originality (Ovando-Tellez et al., 2019). On the contrary, the meta-analyses of brain activity during divergent thinking indicated increased brain activity during divergent thinking compared with the control task in the bilateral lateral prefrontal areas, anterior cingulate cortex, and left temporal and parietal areas as well as decreased brain activity in the right inferior parietal area and precuneus (Wu et al., 2015). Alternatively, greater average originality of divergent thinking tasks were associated with reduced deactivation in the right temporoparietal junction and posterior cingulate cortex (Fink et al., 2014). Further, studies of individual differences in structural connectivity (Kenett et al., 2018) and functional connectivity (Vartanian et al., 2018) have revealed the importance of right inferior frontal junction connectivity for divergent thinking; the former (Kenett et al., 2018) showed that both originality and fluency scores associated with structural connectivity measures.

Taken together, these findings suggest common as well as unique effects of originality of divergent thinking compared with other subscores of divergent thinking. These unique aspects appear to be associated with cognitive mechanisms related to intelligence and attention. In a previous study involving a WM task, we found that the total score of CMT was associated with reduced task-induced deactivation of the posterior part of the default mode network, which is typically deactivated during externally directed attention-demanding tasks (Takeuchi et al., 2011b). However, the

unique associations of individual differences in originality and fluency with attention-related brain activity patterns have not yet been elucidated. Thus, the purpose of the present study was to investigate this issue. For this purpose, we investigated the association between brain activity during an attention-demanding task and originality/fluency score, which have been used for originality-specific effects (additional details of the rationale for using this task is provided in the Methods section).

In this study, we utilized the N-back task during functional magnetic resonance imaging (fMRI) to examine unique brain activity patterns associated with CDMT for following reasons. (1) First, creativity is uniquely related to attentional processes as discussed above and the N-back task is a widely used externally directed attention-demanding task. (2) Second, deactivation in the default mode network (DMN) during the N-back task is widely considered to reflect the efficiency of attentional reallocation (Whitfield-Gabrieli et al., 2009) and its neurochemical correlates are well investigated (Hu et al., 2013). (3) Subjects with ADHD and psychosis, which are traditionally associated with greater creativity and possibly greater originality than fluency, show differences in task-induced deactivation (Ko et al., 2013). (4) The total CDMT score is correlated with task-induced deactivation during the 2-back task, which gives relevance this task to CDMT (Takeuchi et al., 2011b). (5) Psychometric intelligence, which was shown to be more strongly associated with originality than fluency, influences brain activity during the N-back task, including task-induced deactivation (Takeuchi et al., 2018).

On the basis of the relevant above-mentioned lesions studies, we hypothesized that greater activity in the medial prefrontal cortex, right inferior frontal gyrus, and right

temporoparietal areas would be associated with originality of CMDT. In addition, given the associations between originality and intelligence, we hypothesized that brain activity patterns characteristic of high intelligence (i.e., lower activation and deactivation change in response to task demand (Takeuchi et al., 2018)) would be observed in subjects with greater originality.

More specifically, we hypothesized that greater originality is characterized by (a) a lower activation increase in areas of the lateral prefrontal cortex and parts of the lateral parietal cortex showing increased activation during externally directed attention-demanding tasks as well as (b) lower task-induced deactivation in areas of medial prefrontal cortex, precuneus, hippocampus, and temporoparietal junction that are deactivated during externally directed attention-demanding tasks, as in the case of the association between general intelligence and brain activity (Takeuchi et al., 2018).

Further, evidences have also revealed sex differences in neurocognitive correlates of CMDT (Takeuchi et al., 2017b). First, a psychological study reported sex differences in the associations between CMDT and psychopathology, with males showing stronger associations (Martín-Brufau and Corbalán, 2016). Further, males and females use different strategies and cognitive styles during divergent thinking tasks (for review, see Abraham, 2016). For example, males show greater systemizing and a more analytical style, while females tend to show a more empathizing style. Similarly, males and females generate different outputs during free drawing and when generating lyrics to songs. An electrophysiological study also revealed that females show stronger reactivity of α_2 rhythm during verbal divergent thinking than males (Matud et al., 2007), while fMRI during divergent thinking revealed that males recruit regions involved in declarative memory than females, while females recruit regions involved in theory of

mind and self-referencing (for review, see Abraham et al., 2014). Further, structural studies have shown substantial sex differences in connectivity and gray matter structural correlates of CMDT (Ryman et al., 2014; Takeuchi et al., 2017b). Our previous huge-sample study also revealed robust sex differences in the associations between resting-state functional connectivity measures and CMDT (Takeuchi et al., 2017a). Collectively, these neuroimaging, neurophysiological, and neuropsychological studies suggest robust sex differences in neurocognitive correlates of CMDT over a wide range of measures.

However, so far, sex differences in the brain activation correlates of originality compared with fluency have not yet been examined. Thus, we investigated this issue in a large sample. We also assessed the psychological correlates of originality compared with fluency. Specifically, we investigated if representative psychological correlates of CMDT total score observed in our previous studies were associated with originality and/or fluency subscores to reveal distinct psychological correlates of originality versus fluency (originality/fluency) compared with the total CMDT score. Given the important roles of creativity and originality in human culture, we believe that revealing their neural bases is an important topic.

Material and Methods

Subjects

The present study is a part of an ongoing project for investigating the associations among brain imaging, cognitive function, and aging. Data include relevant cognitive measures and neuroimaging data from 1221 healthy right-handed individuals (700 males, 521 females). The mean subject age was 20.7 years (standard deviation [SD], 1.8

years; age range, 18–27 years). For detailed subject information, see Supplemental Methods. See the Supplemental Discussion for the limitations conferred by this cohort. Written informed consent was obtained from all participants or their guardians. This study was approved by the Ethics Committee of Tohoku University.

This study included data from the 63 subjects also included in our previous study investigating the association between total CMDT score and brain activity during the N-back task across males and females (Takeuchi et al., 2011b).

Divergent thinking assessment

The descriptions in this subsection are largely reproduced from our previous study using the same methods (Takeuchi et al., 2017b).

The S-A creativity test (Minds, 1969) was used for assessing CMDT. J.P. Guilford generated the draft plan of this test. He also supervised the development of the test (Minds, 1969). The test was standardized for Japanese speakers (Minds, 1969).

The test is used for evaluating verbal CMDT (Minds, 1969), and it involves three types of tasks: Practice (and real) tasks were administered in the following order: (1) practice of the first task (2 min), (2) first task (5 min), (3) practice of the second task (2 min), (4) second task (5 min), (5) practice of the third task (2 min), and (6) third task (5 min). Each task involves two questions. In total, the test takes 30 min. How subjects divided their time (5 min in total) for two questions was not determined. The 2 questions were presented on 2 facing pages, and on each page there were also 10 lines under the question on which subjects were required to write down self-generated answers.

This test was administered in a group setting. The first task requires subjects to generate unique ways of using typical objects (e.g., “Other than for drinking milk,

how can we use milk bottles?” Example answer: “We can use them as saving boxes.”). The second task requires subjects to imagine desirable functions of ordinary objects (e.g., “What are the characteristics of a good TV? Write down as many characteristics as possible.” Example answer: “A TV can receive broadcasts from all over the world.”). The third task requires subjects to imagine the consequences of “unimaginable things” happening (e.g., “What would happen if all the mice in the world disappeared?” Example answer: “The world would become more hygienic.”). For each task, subjects are required to generate as many answers as possible. Note that these tasks correspond with the three tasks (unusual use, product improvement, just suppose) of the Torrance test of creative thinking (TTCT; Torrance, 1966), which is used in other countries.

Scoring was performed by the Tokyo Shinri Corporation. In addition to a total score, the S-A creativity test provides subscores for the following dimensions of creativity: (a) Fluency: Fluency is measured by the number of relevant responses to questions and is related to the ability to produce and consider several alternatives. Fluency scores are determined by the total number of questions answered after excluding inappropriate responses or responses that are difficult to understand. (b) Flexibility: Flexibility is the ability to produce responses from a wide perspective. Flexibility scores are determined by the sum of the (total) number of category types to which the responses are assigned based on a criteria table or similar judgment. (c) Originality: Originality is the ability to produce ideas that differ from those of others. For originality scoring, each answer was assigned to an idea category from a criteria table or similar judgment. Each category received different originality points based on appearance frequencies, and originality score was calculated as the sum of all these points. In the case of the first task, answers categorized to “containers” had high appearance frequencies (>5%) and so were

awarded 0 points. Alternatively, the answers categorized as “alternatives for musical instruments” had lower appearance frequencies (1%–5%) and so were awarded 1 point, while rarer answer categories or answers that could not be categorized were awarded 2 points. (d) Elaboration: Elaboration is the ability to produce detailed ideas (Society for Creative Mind, 1969). Elaboration scores are determined by the sum of responses weighted based on a criteria table or similar judgment. In the case of the first task, answers that were classified as the lowest level of elaborateness, “unclear answers” such as “musical instruments” (within the “alternatives for musical instruments” category), were awarded 0 points, while answers classified to the middle level of elaborateness, which have typically only means or purposes such as “beat and make sounds” were awarded 1 point, and answers classified as the highest level of elaborateness, which have typically both means and purposes and/or more details such as “arrange milk bottles in a row and put different amounts of water in each bottle and beat to use as instruments” were awarded 2 points. Again, these four dimensions correspond to the TTCT (TTCT; Torrance, 1966). Scoring of the tests was performed by the Tokyo Shinri Corporation.

In the present study, total score and originality/fluency score were used. The total score is the sum of the originality score and elaboration in the S-A creativity test (Minds, 1969) used here (as stipulated by the manual of this test) and is also called as overall score. Strong correlations were noted among fluency, elaboration, and flexibility ($r > 0.78$, in this study), while originality score exhibited a slightly distinctive pattern, with simple correlation coefficients of 0.57–0.72, consistent with the distinctive psychological characteristic of originality/fluency score (see Results). Also, elaboration score tended to be approximately three times higher than the originality score. The average z scores of

the four dimensions and this total score (originality + elaboration) were highly correlated ($r = 0.97$). Originality/fluency score has been used by other researchers (Eisenman, 1969) and represents the originality of answers after adjusting for the number of responses (infrequency of each generated idea). Since the originality score itself is the sum of the originality score of each generated idea, it is directly affected by fluency. Therefore, originality/fluency score was used in this study, consistent with our previous work (Takeuchi et al., 2015d). We used this score also because originality/fluency because this score represents ratio of originality to fluency which corresponds to comparison of originality with fluency and investigating the neural correlates of originality when compared with fluency is the purpose of this study. Further, this score has been used in previous studies conducted at both ours and other labs (Eisenman, 1969; Takeuchi et al., 2015d). This score shows substantial correlation with originality but little correlation with fluency as described in the Results (meaning this score reflects components specific to originality, and does not reflect components specific to fluency), thereby simplifying interpretation. While these are strengths of this score compared to other measures such as z score of originality – z score of fluency, originality/fluency score is strongly correlated with z score originality – z score fluency ($r = 0.87$), so the difference in neural correlates of these two variables are minor. Other methods such as comparing neural correlates of originality with neural correlates of fluency involve the added difficulty of showing that these neural correlates are statistically different in whole brain analyses.

Please refer to the appendix of our previous study for a sample test and additional details on scoring (Takeuchi et al., 2010a).

Each subfactor of the S-A creativity test scores was significantly correlated with other external measures, such as personality factors and problem-solving abilities,

suggesting its ability to predict performance in everyday situations (Shimonaka and Nakazato, 2007). Furthermore, S-A creativity test scores (total score) are significantly correlated with the frequency of visual hypnagogic experiences, which in turn is correlated with the vividness of mental imagery (Watanabe, 1998). Our previous study (Takeuchi et al., 2013a) showed that S-A creativity test scores (total score) were positively correlated with extraversion, novelty seeking, motivational state, and daily physical activity level, which are consistent with reports for other measures of CMDT (Chavez-Eakle et al., 2006; King et al., 1996). The total score on the S-A creativity test was positively correlated with trait creative attitude as measured by self-report in children (Nish and Niwase, 2003), with scores on a modified version of the figure completion test of figural TTCT in children (Ogata, 1976), and with performance on a novel problem-solving task (Ogata, 1976). Each subfactor of the two S-A creativity test tasks was positively correlated with each subfactor of each originally developed chemical divergent thinking creativity test task (e.g., How can you prevent ice which is taken from the refrigerator from melting?) (Wulanqiqige, 2014).

Assessment of psychometric measures of general intelligence. We used Raven's Advanced Progressive Matrix (RAPM) to assess intelligence as well as to adjust for the effect of general intelligence on brain function. For more details on how RAPM was used in our study, please see our previous works (Takeuchi et al., 2010a, b).

Assessment of other psychological measures. We also investigated if representative psychological correlates of CMDT total score revealed in our previous studies were also associated with originality/fluency score and if this score has psychological correlates.

A number of personality traits measured by the Temperament and Character Inventory show robust correlations with CMDT performance, but we found that all of these CMDT correlates were also strongly correlated with the motivation component [in this previous study we used the vigor subscale of the profile of mood states (POMS)](Takeuchi et al., 2015b); therefore, we used the vigor subscale of POMS for the simplicity of the analysis. The descriptions in this subsection are mostly reproduced from our previous studies (Takeuchi et al., 2015a). Psychological measures previously shown to be associated with CMDT are as follows:

- (a) Psychometric intelligence. Originality of CMDT is associated with psychometric intelligence (Jauk et al., 2013). In addition to RAPM, we used the Tanaka B-type intelligence test (TBIT) type 3B (Tanaka et al., 2003) to assess intelligence. This is a nonverbal intelligence test that does not include story problems, but uses figures, single numbers, and letters as stimuli. In all subtests, subjects completed as many problems as possible within a certain time (a few minutes). For details, see **Supplemental Methods**.
- (b) Simple processing speed. CMDT is positively associated with simple processing speed (Preckel et al., 2011). As a measure of simple processing speed, we used the perception factor of the TBIT (Tanaka et al., 2003) type 3B. For details, see **Supplemental Methods**.
- (c) Working memory. WM was assessed using a (computerized) digit span task. For details, see **Supplemental Methods**.
- (d) Motivational state. While a number of personality traits (such as harm avoidance) related to affect are associated with CMDT, motivational state plays an important role in these associations (Takeuchi et al., 2015b). Thus, we focused on motivational

state. We used the vigor subscale of the shortened Japanese version (Yokoyama, 2005) of the Profile of Mood States (POMS) (McNair et al., 1992) to measure participants' motivation during the preceding week.

- (e) Empathizing and systemizing. Empathizing and systemizing are positively associated with CMDT (Takeuchi et al., 2014b). To measure systemizing and empathizing, we used the Japanese versions (Wakabayashi et al., 2007) of the systemizing quotient (SQ) and empathy quotient (EQ) questionnaires (Baron-Cohen et al., 2003; Baron-Cohen and Wheelwright, 2004). EQ score was used as an index of empathizing (drive to identify the mental status of other individuals), while SQ score was used as an index of systemizing (drive to analyze a system). For details, see **Supplemental Methods**.

fMRI task. Functional magnetic resonance imaging (fMRI) was used to map brain activity during cognitive tasks. The descriptions of this task are reproduced from our previous study using the same methods (Takeuchi et al., 2015d). We used the N-back task, which is commonly used in fMRI studies, with conditions of 0-back (simple cognitive processes) and 2-back (WM). We used a simple block design and the N-back WM task (Callicott et al., 1999) to map brain activity during WM. The N-back task was performed during fMRI scanning as previously described (Takeuchi et al., 2011a; Takeuchi et al., 2011b).

Participants received instructions and practiced the tasks before entering the scanner. During scanning, they viewed stimuli on a screen via a mirror mounted on a head coil. Visual stimuli were presented using Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA). A fiber optic light-sensitive key press interface with a button

box was used to record participants' responses during the tasks.

Two conditions were used: 0-back and 2-back. Each condition comprised six blocks, and all N-back tasks were performed in one session. Subjects were instructed to recall visually presented stimuli (four Japanese vowels) presented "n" letters before the currently presented stimulus (e.g., two letters previous for the 2-back task or the currently presented letter for the 0-back task). Two buttons were used during the 0-back task: subjects were asked to push the first button when the defined target stimuli were presented and the second button when non-target stimuli were presented. During the 2-back task, subjects were asked to push the first button when the currently presented stimulus and the stimulus presented two letters previously were the same and to push the second button when the currently presented stimulus and the stimulus presented two letters previously were different. Since the four stimuli were presented randomly, the ratio of matched trials to unmatched trials was 1:3 on average. Our version of the N-back task was designed to require individuals to push buttons continuously during the task period. The task level of the memory load was shown above the stimuli for 2 s before the task started, and remained visible and unchanged during the task period (cue phase). Each letter was presented for 0.5 s and a fixation cross was presented for 1.5 s between items. Each block consisted of 10 stimuli. Thus, each block lasted 20 s. A baseline fixation cross was presented for 13 s between the last task item and the presentation of the next task level of the memory load (start of the cue phase). Thus, the rest period lasted for 15 s (13 s + 2 s). There were six blocks for each condition (2- and 0-back). The descriptions in this subsection are mostly reproduced from another study within the same project that used the exact same methods (Takeuchi et al., 2018).

Sufficient practice was allowed, and we ascertained that subjects understood the tasks

and the strategy of updating items to remember two by two during the 2-back task (Takeuchi et al., 2012a). Reaction time (RT) and accuracy on the 0-back and 2-back tasks were used in the analyses.

We designed the task difficulty so that the subjects would make few errors because as task difficulty increases, brain activation changes become larger, but when the task becomes too difficult, and accuracy substantially drops from 100%, such activation changes become smaller, and the resulting inverted u-curve association between task-load and brain activity (Callicott et al., 2003; Jansma et al., 2004) can make linear analyses difficult.

Image acquisition. MRI data acquisition was conducted using a 3T Philips Achieva scanner. Forty-two transaxial gradient-echo images (echo time, 30 ms; flip angle, 90°; slice thickness, 3 mm; FOV, 192 mm; matrix, 64 × 64) covering the entire brain were acquired at a repetition time of 2.5 s using an echo-planar sequence. For the N-back session, 174 functional volumes were obtained. Diffusion-weighted data were acquired using a spin-echo echo-planar imaging (EPI) sequence according to a previously described protocol (Takeuchi et al., 2015b). From the collected images, fractional anisotropy (FA) and mean diffusivity (MD) maps were calculated (Takeuchi et al., 2011c). In this study, these FA and MD maps were used during preprocessing of BOLD images as described in the following sections. The descriptions of this subsection are mostly reproduced from our previous study using the exact same methods (Takeuchi et al., 2015d).

Preprocessing of imaging data

Preprocessing and analysis of functional activation data were performed using SPM8 implemented in MATLAB. A summary is provided here; see the **Supplemental Methods** for more details. Before analysis, individual BOLD images were realigned and re-sliced to the mean BOLD image and corrected for slice timing. The mean BOLD image was then realigned to the mean $b = 0$ image as previously described together with slice timing corrected images (Takeuchi et al., 2011b). As the mean $b = 0$ image was aligned with the FA image and MD map, the BOLD image, $b = 0$ image, FA image, and MD map were all aligned. All images were normalized using a previously validated two-step “new segmentation” algorithm of diffusion images and the previously validated twisted diffeomorphic anatomical registration through exponentiated lie algebra (DARTEL)-based registration (Takeuchi et al., 2013b). The voxel size of the normalized BOLD images was $3 \times 3 \times 3 \text{ mm}^3$. The descriptions in this subsection are mostly reproduced from our previous study using the exact same methods (Takeuchi et al., 2018).

This preprocessing procedure utilizes the information of both FA and MD maps for segmentation and the FA signal distribution within white matter for the DARTEL. The reasons for utilizing FA and MD maps for preprocessing are as follows. The diffusion tensor images have similar anatomical characteristics as BOLD images but more detailed anatomical information. Further, MD maps are suitable for dissociating cerebrospinal fluid from tissue and gray from white matter, while FA maps are suitable for dissociating gray and white matter areas. Also, by accounting for FA signal variability within white matter areas in the DARTEL, misalignment of the tracts was prevented. For the validation of these issues, see our previous study (Takeuchi et al., 2013b).

First-level analysis of functional activation data

Individual-level statistical analyses were performed using a general linear model. A design matrix was fitted to each participant with one regressor in each N-back task condition using the standard hemodynamic response function. The cue phases of the N-back task were modeled in the same manner, but were not analyzed further. Six parameters obtained by rigid body correction of head motion were regressed out by inclusion in the regression model. The design matrix weighted each raw image according to its overall variability to reduce the impact of movement artifacts (Diedrichsen and Shadmehr, 2005). We removed low-frequency fluctuations using a high-pass filter with a cut-off value of 128 s. After estimation, beta images of the 0-back task, 2-back task, and the contrast of (2-back – 0-back) were smoothed (8 mm full-width at half-maximum) and taken to the second level of analysis. The descriptions in this subsection are mostly reproduced from our previous study using the exact same methods (Takeuchi et al., 2015d).

Image smoothing was performed after estimation (instead of before estimation) because the abovementioned method (Diedrichsen and Shadmehr, 2005) works slightly better on unsmoothed data, so that it has more independent data points to estimate the variance of the images. And the developers recommend not smoothing the raw data before estimation, but instead to smooth the beta-weights before submitting them to the second-level analysis (see the page for the distribution, http://www.diedrichsenlab.org/imaging/robustWLS_spm8.html).

Statistical analysis of psychological variables

Behavioral data were analyzed using SPSS 22.0 (SPSS Inc., Chicago, IL). The correlations among basic variables (total scores, subscores, originality/fluency scores, RT of the 0-back task, RT of the 2-back task, and RT difference between the 2-back task and the 0-back task) in each sex were analyzed by simple correlation analyses.

The main effects as well as interaction effects between sex and originality/fluency score on cognitive measures were analyzed using analysis of covariance (ANCOVA). Sex was a fixed factor and the additional covariates were age, RAPM score, and originality/fluency score on the S-A creativity test. The abovementioned covariates and the interaction between sex and originality/fluency score were included in the model. The dependent variables were the seven psychological variables listed in Table 1. We also conducted ANCOVAs of the same models, except that the originality/fluency score was replaced by the total score on the S-A Creativity test, and the results are provided in the Supplemental Results section and in the Supplemental Table 2. In total, 14 ANCOVAs (7 dependent variables \times 2 CMDT scores [total score and originality/fluency score] = 14) were performed in this study (the analyses that were presented in the main text and the Supplemental Online Material section). In the psychological variable analyses, results with a threshold of $p < 0.05$, corrected for false discovery rate (FDR) using the two-stage sharpened method (Benjamini et al., 2006), were considered statistically significant. Correction for multiple comparisons using this method was applied to the results for main effects and interaction effects with sex in the abovementioned 14 ANCOVAs (28 p values). The descriptions in this subsection were largely reproduced from our previous study using similar methods (Takeuchi et al., 2015c).

Group-level whole-brain imaging data analyses.

At the group level, we tested the effects of originality/fluency score on regional brain activity during the 0-back and 2-back tasks, as well as WM-specific regional activity (2-back–0-back contrast). Group-level whole-brain imaging analyses were performed using SPM8. In these analyses, we used voxel-wise ANCOVA with sex difference as a grouping factor (using the full factorial option in SPM8). The covariates were age, RAPM score, accuracy, RTs on the 2-back task and 0-back task, and volume-level mean framewise displacement during the scan for the N-back task (Power et al., 2012) and originality/fluency score. We also conducted voxel-wise ANCOVAs of the same models, except that the originality/fluency score was replaced by total S-A Creativity test score and results were provided in the Supplemental Results section and in the Supplemental Table 3 and 4 and Supplemental Fig. 2 and 3. In total, six brain analyses were conducted (3 contrasts [0-back task, 2-back task, and 2-back–0-back] \times 2 scores [total score and originality/fluency score] = 6) in this study (The analyses that were presented in the main text and the Supplemental Online Material section). All contrasts involving the task conditions were used in this study. The 0-back task contrast represents simple cognitive processes, the 2-back task contrast represents activity during WM, and the 2-back to 0-back task contrast represent WM-specific cognitive activity. All the conditions involve continuous externally directed attention (in accordance with the study purpose), but the two-back condition involves WM and attention demand. Task performance and movement during the scan were added as covariates to rule out the possibilities of behavioral differences affecting the correlations between brain activity patterns and target psychometric variables. See the Supplemental Methods for an explanation on adding RAPM score as a covariate and the influences of removing

RAPM from the covariate set on the results.

The covariates were modeled such that each had a unique relationship with functional activity for each sex (using the interactions option in SPM8), except for framewise displacement during scanning, which enabled investigation of the effects of interaction between sex and each covariate. Framewise displacement during scanning was not modeled in this manner as a common effect on functional activity was assumed for both sexes.

The main effects of S-A creativity test scores (contrasts of [effect of S-A creativity test score for males, females] were [1 1] or [-1 -1]) and the interaction between sex and S-A creativity test scores (contrasts of [effect of S-A creativity test for males, females] were [-1 1] or [1-1]) were assessed using t contrasts.

Correction for multiple comparisons was performed using the threshold free cluster enhancement (TFCE) score with randomized (5,000 permutations) nonparametric testing using the toolbox (<http://dbm.neuro.uni-jena.de/tfce/>). We applied a voxel threshold of family-wise error (FWE) corrected at $P < 0.05$.

The areas of activation and deactivation under the corresponding task condition (i.e., in the case of 0-back analyses, activity/deactivation during the 0-back task) were defined through the lenient threshold of $P < 0.05$ (false discovery rate (FDR)-corrected at the voxel level among the analyses of one-sample t tests using the whole subjects. This threshold was used to classify voxels to areas of significant effects of CMDT scores on activation and deactivation.

Results

Psychological scores

Table 1 presents the correlations among basic variables, including total score, originality/fluency scores, subscores of S-A creativity test, RTs on the 0-back and 2-back tasks, and difference in the RT of 0-back task and 2-back task for each sex. Distributions of originality/fluency scores and total scores on the S-A creativity test are presented in Fig. 1 and Supplemental Fig. 1. Originality/fluency score showed little correlation with fluency subscores ($r = 0.033$ in males, $r = -0.007$ in females), while showing substantial correlations with originality scores ($r = 0.719$ in males, $r = 0.783$ in females). Response accuracies on the 2-back and 0-back tasks showed ceiling effects ($>99.0\%$ correct on average).

Mean (\pm SD) age, RAPM score, total score, subscores, originality/fluency score on the S-A creativity test, accuracies and RTs for the 0-back and 2-back tasks, and volume-wise framewise displacement are presented in Supplemental Table 1.

Psychological main effects and interactions of originality/fluency score

ANCOVA revealed significant main effects of originality/fluency score on RAPM, total score on TBIT, perception factor score on TBIT, and SQ score. The correlation of originality/fluency with psychometric intelligence score is consistent with a previous study reporting that psychometric intelligence is correlated more strongly with originality than with fluency of divergent thinking (Jauk et al., 2013). However, originality/fluency score showed little correlation with empathizing and vigor subscales of the POMS, suggesting the unique characteristics of originality/fluency score compared with the total CMDT score (See Supplemental Table 2 for the results found in this study).

ANCOVA also revealed a significant interaction between sex and

originality/fluency on perception factor score of TBIT (stronger positive correlation in females than males). See Table 2 for full results.

Main effects of originality/fluency score on the S-A creativity test on functional activation

ANCOVA revealed an overall positive main effect (regardless of sex) of originality/fluency score on the S-A creativity test on functional activity during the 0-back task in a cluster mainly around the right angular gyrus, right calcarine cortex, right cuneus, right fusiform gyrus, right occipital lobe, parahippocampal gyrus, right parietal cortex, precentral and postcentral gyrus, right precuneus, right supramarginal gyrus, right superior, and middle and inferior temporal gyrus (54.5% and 36.5% of this large cluster belong to areas activated and deactivated during the 0-back task, respectively), and in a cluster involving the right fusiform gyrus and right cerebellum (all of this cluster belongs to areas deactivated during the 0-back task) (Fig. 2a).

In addition, ANCOVA revealed an overall positive main effect (regardless of sex) of originality/fluency score on the S-A creativity test on functional activity during the 2-back task in a cluster mainly around the bilateral amygdala, bilateral calcarine cortex, bilateral posterior and middle cingulate gyrus, bilateral cuneus and precuneus, right superior, middle, and inferior orbital frontal gyrus, bilateral fusiform gyrus, right Heschl's gyrus, bilateral hippocampus, parahippocampal gyrus, right insula, bilateral lingual gyrus, bilateral inferior, middle, and superior occipital lobe, bilateral paracentral lobule, bilateral superior parietal lobe, bilateral postcentral gyrus, right precentral gyrus, right putamen, right rolandic operculum, right supplemental motor area, bilateral middle and inferior temporal gyrus, right superior temporal gyrus and temporal pole, bilateral

thalamus, and bilateral cerebellum (24.1% and 70.4% of this large cluster belong to areas activated and deactivated during the 2-back task, respectively); a cluster mainly around the dorsomedial prefrontal cortex and contingent anatomical areas (all voxels in this cluster belong to areas deactivated during the 2-back task); and small clusters in the left middle frontal gyrus and left precentral gyrus (Fig. 2b).

ANCOVA revealed an overall positive main effect (regardless of sex) of originality/fluency score on the S-A creativity test on functional activity of the contrast (2-back – 0-back) in a cluster mainly around the dorsomedial prefrontal cortex and contingent left middle and superior frontal gyrus (all areas in this cluster belong to areas deactivated in the corresponding contrast); a cluster spread around the middle and posterior cingulate gyrus, precuneus, cuneus, and bilateral calcarine cortex (all areas in this cluster belong to areas deactivated in the corresponding contrast); a cluster spread around the right hippocampus, parahippocampal gyrus, and right lingual gyrus (23.9% and 43.5% of this large cluster belong to areas activated and deactivated in the corresponding contrast, respectively); and clusters spread around the anterior cingulate gyrus, middle cingulate gyrus, and medial frontal gyrus (all areas in these clusters belong to areas deactivated in the corresponding contrast) (Fig. 2c). For full statistical results, see Table 3.

Interaction effect of sex and originality/fluency scores on functional activation

ANCOVA revealed an interaction effect between sex and originality/fluency score on the S-A creativity test on functional activity during the 0-back task in a cluster that mainly spread around the left angular gyrus, bilateral calcarine cortices, bilateral middle and posterior cingulate gyrus, bilateral precuneus and cuneus, bilateral lingual

gyrus, bilateral occipital lobes, bilateral paracentral lobule, bilateral postcentral gyrus, bilateral supplemental motor area, left supramarginal gyrus, left middle and superior temporal gyrus, right superior parietal lobule, and left rolandic operculum (19.0% and 71.9% of this large cluster belong to areas activated and deactivated during the 0-back task, respectively); a cluster spread mainly around the left temporal pole and middle temporal gyrus (25.6% and 41.1% of this large cluster belong to areas activated and deactivated during the 0-back task, respectively); a cluster spread mainly in the hippocampus and left parahippocampal gyrus (19.1% and 55.3% of this large cluster belong to areas activated and deactivated during the 0-back task, respectively); and a cluster spread mainly in the left thalamus (most voxels in this cluster belong to areas activated during the 0-back task). These interactions were formed with the positive correlation in males and negative correlations in females (Fig.3).

ANCOVA also revealed an interaction effect between sex and originality/fluency score on the S-A creativity test on functional activity of the contrast [2-back – 0-back] in a cluster spread mainly around the left inferior and superior parietal lobules, left angular gyrus, and left precuneus (most voxels in this cluster belong to areas activated in this contrast). These interactions were negatively correlated in males and positively correlated in females.

For full statistical results, see Table 4.

Discussion

The present study has revealed new associations between originality/fluency score and functional activity, as well as sex differences in the associations between originality/fluency scores and functional activity. Although there were numerous

contrasts and some of the findings were sporadic, the major results can be summarized as follows. Partly consistent with our first hypothesis, originality/fluency scores were significantly positively correlated with activity in the right temporoparietal area during the 0-back and 2-back tasks, activity in the right inferior frontal gyrus during the 2-back task, and activity in the medial prefrontal cortex during the 2-back task and the contrast of (2-back – 0-back). Partly consistent with our hypothesis, subjects with greater originality/fluency scores showed lower task-induced deactivation in areas deactivated during the task, including the right precentral gyrus (0-back, 2-back), medial prefrontal cortex, posterior cingulate cortex, precuneus, right medial temporal lobe, (2-back, 2-back – 0-back), and right temporal area (2-back). However, in contrast with our hypothesis, associations between greater originality/fluency scores and lower task-related activation increases were not observed. Further, there were significant interaction effects between sex and originality/fluency scores, on activity during the 0-back task (mediated by positive correlations in males and negative correlations in females) in the left precentral and postcentral gyrus. Further, interactions between sex and originality/fluency scores on activity during the 0-back task were observed in extensive deactivated areas, including the posterior cingulate cortex, precuneus, left temporoparietal junction and, left temporal pole. Across the sexes, greater total CMDT scores were associated with lower task-induced deactivation in the posterior part of the DMN, which was consistent with our previous study, and were also associated with greater activity in extensive areas of the right temporoparietal junction and right inferior frontal gyrus during the 0-back task and 2-back task. Lastly, across the sexes, originality/fluency scores were positively correlated with measures of psychometric intelligence, simple processing speed, and systemizing (although the association with

simple processing speed was female-specific). The lower correlation coefficients between brain activity and CMDT scores, as shown in the figures, are not indicative of the low importance of the observed associations; low correlations are typical in studies of associations between cognitive variables and neuroimaging measures with large sample sizes (Takeuchi and Kawashima, 2019). See the Supplemental Discussion for more on this issue.

Brain activity in the anterior part of the right temporoparietal junction, right superior temporal gyrus, and ventral prefrontal cortex was positively correlated with originality/fluency score on the CMDT across the 0-back simple cognitive task and 2-back WM task, and also the total CMDT score showed similar patterns (see Supplemental Results section). These areas of the right hemisphere form the ventral attention system (Corbetta et al., 2008) and are involved in reorienting attention to outside events or switching attention between different matters and networks (Corbetta et al., 2008). Suppression of this network is thought to reflect a filtering signal that gates sensory responses by behavioral relevance (Corbetta et al., 2008). When subjects focus on a task, deactivation of this network is thought to prevent reorientation to unimportant objects (Corbetta et al., 2008). Therefore, relatively greater activity in these areas reflects conditions where subjects are easily distracted and reoriented to unimportant objects and one are not filtering the unimportant objects completely. These findings may be consistent with previous studies reporting that creative subjects have insufficient selective attention (Necka, 1999) and insufficient ability to ignore irrelevant external stimuli (Kasof, 1997). Hyperactive children, who are characterized by a decreased ability to easily focus their attention, tend to show greater creativity (Kuntsi et al., 2001) and administration of the drug Ritalin reduces ADHD symptoms and creativity

(Swartwood et al., 2003). It has been suggested that greater creativity might be achieved using different brain networks, which represent knowledge in one domain to help organize a quite different domain that might, nevertheless, share some attributes (Heilman et al., 2003). Tendency to frequently switching attention between different networks or incorporate seemingly unimportant matters may lead one to rare ideas, thereby achieving originality and creativity. However, this study did not utilize measures of behavioral distractibility. As these ideas are reverse inference and speculations, confirmatory studies are needed.

Besides the right ventral attention network, originality/fluency scores showed positive correlation with brain activity in areas deactivated during externally-directed attention-demanding tasks (meaning greater originality/fluency scores were associated with smaller task-induced deactivation in the DMN). Although total creativity score was positively correlated with a part of the posterior DMN, which is consistent with our previous study (Takeuchi et al., 2011b), originality/fluency scores showed clear and widespread correlations. We previously suggested that reduced TID in the DMN in creative subjects (based on total score) reflected inefficient reallocation, partly because the magnitude of TID in the DMN is characteristic of subjects with reduced WMC, such as relatives of schizophrenia patients and the elderly (Sambataro et al., 2010; Whitfield-Gabrieli et al., 2009), whereas schizotypy is characterized by facilitated creativity and impaired WM capacity (Fisher et al., 2004; Horan et al., 2008; Matheson and Langdon, 2008). Low TID of the DMN is reportedly underlain by brain excitability/inhibition mediated by glutamate and GABA (Hu et al., 2013), which are characteristics of patients with schizophrenia (Lewis et al., 2012). However, in the present study, originality/fluency scores were positively correlated with psychometric

intelligence (and tended to be positively correlated with WM performance). Our previous study showed an association between greater psychometric intelligence and reduced TID in the DMN (Takeuchi et al., 2018). Considering that TID is smaller in tasks with low cognitive demand (McKiernan et al., 2003), from this perspective, reduced TID in the DMN may be indicative of lower cognitive demand being experienced by subjects, and thus greater cognitive competence. Consistent with this notion, we previously reported that the risk allele of the dopamine receptor D4 gene for ADHD was associated with reduced TID in the DMN and, specifically, greater originality among CMDT subscales (Takeuchi et al., 2015d). However, brain activity of intelligent subjects was also characterized by lower activation increases in areas activated during the tasks, which was not observed in subjects with greater originality/fluency score in this study (Takeuchi et al., 2018). Considering that characteristics of subjects with specifically greater originality in CMDT may not be same as those of schizotypy (low TID, signs of worse performance and excitability) nor subjects with greater intelligence (low TID, low activation, better performance). Other factors, such as greater cognitive speed (as confirmed in the present study), could compensate for inefficient attentional reallocation underlain by greater neural excitability in such subjects.

These correlations of divergent thinking performance with brain activity patterns in the DMN during the externally directed attention-demanding task are consistent with previous neuroimaging findings showing associations between CMDT and changes in DMN activity patterns. For example, Beaty et al. (2015) reported coupling of the DMN and executive control network during the alternate uses divergent thinking task compared to the control task condition. Further, resting-state fMRI studies

have reported that the functional connectivity of various areas involving the DMN are associated with higher creativity as measured by alternate uses tasks and other divergent thinking tasks (Beaty et al., 2014), the S-A creativity test employed in the present study (Takeuchi et al., 2012b), and the verbal TTCT test (Beaty et al., 2014). Jung et al. (2010) also reported that cortical thickness at the temporoparietal junction, which is part of the DMN, is negatively associated with greater CMDT performance as measured by a composite creativity index composed of three divergent thinking task scores. Further, reduced task-induced deactivation in precuneus and right temporoparietal junction during a divergent thinking task (alternate uses task) was associated with greater originality on the task (Fink et al., 2014). Also, Mayseless et al. (2015) reported that brain activation in the ventral anterior cingulate areas of the DMN was positively correlated with average originality in the alternative uses task compared with a control task. The present results further extend this finding of greater activity in the DMN among subjects with greater originality (relative to fluency) during an externally directed attention-demanding task that does not involve divergent thinking, and supports the specific involvement of originality and the attentional process itself (rather than cognitive processes recruited for divergent thinking) in the associations between DMN and divergent thinking.

In psychological analyses, although the psychological correlates of total CMDT scores that were previously reported and are presented in Supplemental Table 2, and psychological correlates of originality/fluency scores overlapped, the psychological correlates of originality/fluency scores are limited to “cognitive” aspects (cognitive functions and systemizing, which is a drive to analyze a system), and did not include empathizing (social components) or motivational states (affective components). The

specific association of originality with psychometric intelligence was consistent with previous studies (Jauk et al., 2013). Interestingly, originality/fluency scores did not correlate with fluency of CMDT, but did show significant positive correlations with cognitive speed (total score and perception factor score on TBIT, although the latter correlations seem to be specific to females), which is an advancement of the present study. Thus, while the ADHD risk was specifically associated with originality (Takeuchi et al., 2015d), superior basic cognitive abilities, including psychometric intelligence measured by nonverbal reasoning and cognitive speed, may also contribute to generate original ideas in CMDT. Furthermore, associations of originality/fluency score with systemizing suggest that by analyzing a system, subjects with higher systemizing may be able to generate original ideas. This relationship could explain the creative achievements by individuals with autistic characteristics in certain areas (Baron-Cohen, 2003).

Furthermore, interaction effects between sex and CMDT scores on brain activity were observed, especially during the 0-back task. The mechanisms underlying these associations are not clear. However, our psychological analyses revealed significantly greater associations between originality/fluency scores and simple processing speed among females, who also tended to show greater associations between total CMDT scores and simple processing speed (Supplemental Table 2). These findings may coincide with female-specific positive correlations between total CMDT scores and regional white matter volume (Takeuchi et al., 2017b), which is in turn associated with simple processing speed (Magistro et al., 2015). The significant interaction between sex and originality/fluency scores and total CMDT scores in the left precentral and postcentral gyrus (Supplemental Fig. 3) may be due to the greater speed in subjects with

greater originality, which may be associated with greater neural efficiency in females in sensorimotor areas. On the other hand, in addition to differences in precentral and postcentral areas, females with greater originality/fluency scores showed lower TID in extensive areas of the posterior part of the DMN in the 0-back task. Given that the 0-back task is simple enough for highly-educated young adult samples, greater TID in the DMN may reflect efficient attentional reallocation (Whitfield-Gabrieli et al., 2009). It is possible that subjects with greater originality/fluency scores tend to focus on simple cognitive tasks and thus achieve better performance on simple cognitive tasks (but not cognitively-demanding WM tasks). However, the present study lacks data to confirm these speculations.

The present brain imaging results of the total CMDT score offered an opportunity to compare the neural correlates of CMDT with the neural correlates of fluid intelligence as measured by nonverbal reasoning (RAPM). In our previous study (Takeuchi et al., 2018) including almost the same cohort, the associations between high RAPM score and brain activity were generally characterized by (a) lower task-induced deactivation in areas normally deactivated during 0-back, 2-back, and 2-back – 0-back tasks (which did not include temporoparietal junction areas), (b) a lower activation increase in areas normally activated during these same tasks, and (c) a greater increase in the pre-supplementary motor area during the 2-back task. These patterns are similar regardless of whether the total CMDT score is added as a covariate, and total CMDT score was not significantly correlated with RAPM score (Table 2). The present results showing correlations between brain activation patterns and total CMDT score are in accord with our previous findings of correlations between RAPM and brain activity (see (a) above) as both correlates involve lower task-induced deactivation in areas close to

the posterior cingulate cortex. However, the two correlates are otherwise distinct, consistent with the notion that CMDT and psychometric intelligence are mainly independent (Sternberg, 2005).

Another interesting psychological finding is that originality/fluency score did not show any correlation with fluency, indicating that there is no trade-off with fluency and that the more one tends to generate ideas, the more original ideas are generated. This finding appears consistent with the “equal-odds rule” of creativity, suggesting that the more output one produces, the better the chance that one idea generates impacting products and the most prolific ones have the same likelihood of success as do the least productive, on a product-for-product basis (Simonton, 1994). The application to this rule to divergent thinking productions was suggested by Jung et al. using another scoring method (Jung et al., 2015); they used the holistic score obtained by the Consensual Assessment Technique (Amabile, 1982) and snapshot scoring method (Silvia et al., 2009) wherein all six subject responses were given a single holistic score by three judges and yielded a positive linear relationship between fluency and holistic score. Although we used different scoring methods and originality (reflecting statistical infrequency) as described in Methods, our present findings may be in line with these previous findings of the “equal-odds rule” of creativity.

This study is subject to several limitations. First, like many studies in this field, we used a sample of highly-educated young adults (Jung et al., 2010; Li et al., 2014). In such highly-educated samples, associations among higher-order cognitive abilities (such as intelligence) tend to be lower (Engle et al., 1999; Takeuchi et al., 2018). However, it is known that creativity is associated with psychometric intelligence under a certain threshold of intelligence (Sternberg, 2005), and focusing on a highly-educated sample

may be necessary to disentangle the complex relationship between CMDT and higher-order cognitive abilities. Future studies focusing on the general population may be necessary to determine if the present findings are generalizable. Further, it is known that the psychometric characteristics of CMDT are affected by the task instructions (Benedek et al., 2013; Niu and Liu, 2009; Silvia et al., 2013). In the present study, we focused on the traditional instruction of “generate as many ideas as possible”. Future studies may be required to determine if other types of instructions, such as focusing on the quality of the ideas, generate other psychological profiles of CMDT.

Among relevant studies in diverse fields, previous studies have revealed that originality of CMDT is specifically associated with psychometric intelligence. The present study not only confirmed these findings, but further revealed that originality/fluency score is positively correlated with systemizing and simple processing speed (the latter relationship in females only). From the perspective of brain activity during externally-directed attention-demanding tasks, our previous study revealed that total CMDT score was associated with reduced TID in the DMN with a cluster size test shown to be anticonservative. The present study used more than 1200 subjects and permutation-based statistics which are shown to properly control false positives to reveal the brain activity correlates of originality/fluency scores. We also confirmed interaction effects between sex and CMDT scores on neural activity using this large sample size, consistent with the growing body of literature reporting interactions between sex and CMDT scores on neural mechanisms. These represent important contributions of the present study over previous work.

Originality/fluency scores were associated with greater brain activity during the 0-back simple cognitive task and 2-back WM task in key nodes of the ventral attention

system (Corbetta et al., 2008), which is located in the right hemisphere and is involved in reorienting attention. Like subjects with greater psychometric intelligence, subjects with greater originality/fluency scores showed lower task-induced deactivation in areas of the DMN, especially during WM performance. However, unlike subjects with greater psychometric intelligence, subjects with greater originality/fluency scores did not show lower task-related increases in areas activated during externally-directed attention-demanding tasks. Furthermore, interaction effects between sex and originality/fluency scores, on functional activity during the 0-back task were observed—especially in sensorimotor areas. This finding may be ascribed to greater associations between simple processing speed and CMDT scores in females than in males. Lastly, psychological analyses showed that originality/fluency scores were associated with psychometric intelligence and systemizing, but not with social and affective correlates of total CMDT scores.

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Ethical statement

i. Compliance with Ethical Standards: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

ii. Funding: This study was supported by JST/RISTEX, JST/CREST, a Grant-in-Aid for Young Scientists (B) (KAKENHI 23700306) and a Grant-in-Aid for Young Scientists (A) (KAKENHI 25700012) from the Ministry of Education, Culture, Sports, Science, and Technology.

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

iv. Ethical approval: This study was approved by the Ethics Committee of Tohoku University.

v. Informed consent: Informed consent was obtained from all individual participants included in the study.

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Table 1. Matrix of statistical results (simple correlation coefficients and *P* values) of simple correlation analyses performed for basic psychological variables of males (upper side) and females (lower side).

	1	2	3	4	5	6	7	8	9
1, S-A creativity test		0.245	0.782	0.885	0.856	0.968	-0.046	-0.012	0.009
total	-	4.80×10^{-11}	9.65×10^{-146}	1.46×10^{-233}	4.25×10^{-202}	0*	0.227	0.745	0.814
2, S-A creativity	0.281		0.719	0.033	0.179	0.026	0.008	0.008	0.006
Originality/fluency	6.46×10^{-11}	-	1.86×10^{-112}	0.390	1.92×10^{-6}	0.485	0.831	0.827	0.873
3, S-A creativity	0.751	0.783		0.627	0.736	0.603	0.002	0.018	0.022
originality	1.36×10^{-95}	3.44×10^{-109}	-	7.09×10^{-78}	3.53×10^{-120}	2.07×10^{-70}	0.956	0.630	0.566
4, S-A creativity	0.886	-0.007	0.579		0.874	0.883	-0.032	0.002	0.020
fluency	6.15×10^{-175}	0.865	6.01×10^{-48}	-	2.67×10^{-221}	3.71×10^{-231}	0.400	0.952	0.600
5, S-A creativity	0.825	0.236	0.697	0.853		0.803	-0.057	-0.032	-0.010
flexibility	1.63×10^{-130}	1.96×10^{-8}	6.73×10^{-77}	6.51×10^{-149}	-	9.94×10^{-159}	0.133	0.391	0.783
6, S-A creativity	0.963	0.040	0.549	0.888	0.761	-	-0.059	-0.023	0.003
elaboration	2.24×10^{-298}	0.362	2.48×10^{-42}	1.44×10^{-177}	8.94×10^{-100}		0.116	0.542	0.942
	-0.022	-0.024	-0.043	-0.007	-0.046	-0.010	-	0.640	0.269
7, 0-back RT	0.615	0.578	0.329	0.868	0.294	0.812		5.99×10^{-82}	4.45×10^{-13}

	-0.071	-0.045	-0.015	-0.078	-0.078	-0.049	0.580	-	0.912
8, 2-back RT	0.106	0.306	0.016	0.074	0.075	0.246	3.89×10^{-48}		1.06×10^{-272}
9, 2-back RT	-0.074	-0.042	-0.015	-0.091	-0.070	-0.054	0.184	0.908	-
- 0-back RT	0.091	0.344	0.017	0.038	0.108	0.221	2.27×10^{-5}	7.25×10^{-198}	

*P values are too small and the software returns a value of "0".

This matrix table was constructed to reveal distinct correlation patterns among variables between males and females.

Table 2. Main and interaction effects of ANCOVAs for originality/fluency scores on psychological measures.

	Originality/fluency score			
	Main effect	Interaction	Male	Female
	[F score,	[F score,	correlation	correlation
	P value (unc), P value (FDR)]	P value (unc), P value (FDR)]	(r)	(r)
RAPM	5.28	0.35	0.086	0.046
(M:700, F:521)	0.022	0.553		
	0.046*	0.460		
TBIT-Total score	7.56	1.69	0.044	0.126-
(M:635, F:468)	0.006	0.194		
	0.016*	0.217		
TBIT-Perception	7.46	5.73	0.010	0.162
speed factor	0.006	0.017		
(M:635, F:468)	0.016*	0.040*		

Digit span	3.91	3.37	0.004	0.117
(M:635, F:468)	0.048	0.067		
	0.084	0.101		
Vigor scale of	0.76	1.64	0.064	-0.006
POMS	0.385	0.200		
(M:656, F:486)	0.368	0.217		
Empathizing	0.26	0.63	0.009	-0.024
(M:700, F:521)	0.613	0.428		
	0.460	0.391		
Systemizing	14.02	1.60	0.139	0.084
(M:700, F:521)	1.89×10^{-4}	0.207		
	$6.62 \times 10^{-4*}$	0.217		

Table 3. Brain regions showing significant main effects of originality/fluency scores on the S-A creativity test on brain activity.

Including gray matter areas*	x	y	z	TFCE score	Corrected P value (FWE, TFCE)	Cluster size (voxels)	activated/deactivated**	r*** (male/female)
Positive main effect of originality/fluency on activity during the 0-back task								
Angular gyrus (R)/Calcarine Cortex (R)/Cuneus (R)/ Inferior parietal lobule (R)/Superior parietal lobule (R)/Postcentral gyrus (R)/Precentral gyrus (R)/Precuneus (R)/ Supramarginal gyrus (R)/ Middle temporal gyrus (R)/ Superior temporal gyrus (R)/	36	-57	9	816.83	0.0054	2938	1601/1073	0.163/0.111
Fusiform gyrus (R)/Cerebellum (R)/	27	-69	-21	459.23	0.0466	26	26/0	0.087/0.079
Positive main effect of originality/fluency on activity during the 2-back task								
Calcarine Cortex (B)/ Middle cingulum (B)/Posterior cingulum (B)/Cuneus (B)/Inferior frontal orbital area (R)/Fusiform gyrus (B)/Heschl's gyrus (R)/Hippocampus (B)/Insula (R)/Lingual gyrus (B)/Inferior occipital lobe (B)/Middle occipital lobe (B)/Superior occipital lobe (B)/Paracentral lobule (B)/Parahippocampal gyrus (B)/Superior parietal lobule (B)/Postcentral gyrus (B)/Precentral gyrus (R)/Precuneus (B)/ Supplemental motor area (B)/Inferior temporal gyrus (B)/Middle temporal gyrus (B)/Temporal pole (R)/Superior temporal gyrus (R)/Thalamus (B)/Cerebellum (B)/ Anterior cingulum (B)/ Superior frontal medial area (B)/ Superior frontal other areas (B)/	-3	-63	24	826.33	0.002	5686	1368/4001	0.161/0.137
Middle frontal other areas (L)/	-30	60	6	438.42	0.046	1	1/0	0.061/0.065
Precentral gyrus (L)/	-18	-27	60	438.42	0.046	2	0/2	0.049/0.065
Positive main effect of originality/fluency on activity of the contrast (2-back – 0-back)								

Superior frontal medial area (B)/Superior frontal other areas (B)/	-15	51	24	616.04	0.0142	350	0/350	0.128/0.135
Calcarine Cortex (B)/ Posterior cingulum (L)/Cuneus (B)/ Precuneus (B)/	0	-66	24	559.27	0.0206	291	0/291	0.110/0.152
Hippocampus (R)/Lingual gyrus (R)/Parahippocampal gyrus (R)/	21	-18	-18	482.89	0.0356	46	11/20	0.076/0.181
Anterior cingulum (B)/	3	36	18	475.2	0.0388	46	0/46	0.039/0.161
Middle frontal medial area (L)/	0	60	-6	454.31	0.0442	1	0/1	0.082/0.104
Middle cingulum (L)/	-15	-45	36	444.22	0.047	3	0/3	0.035/0.157

*Labeling of the anatomical regions of gray matter is based on the WFU PickAtlas Tool

(<http://www.fmri.wfubmc.edu/cms/software#PickAtlas/>) (Maldjian et al., 2004; Maldjian et al., 2003) and the PickAtlas automated anatomical labeling atlas option (Tzourio-Mazoyer et al., 2002). In this atlas, temporal pole areas and some other areas include all subregions. Areas of the superior frontal other areas include areas of the superior frontal gyrus other than the medial, orbital, and medial-orbital parts of the superior frontal gyrus. Only areas with significant voxels comprising 10% or more of the cluster or areas with 50 or more significant voxels that existed in the cluster were reported.

**Percentage of voxels activated or deactivated during the corresponding condition (i.e., in the case of 0-back analyses, activity/deactivation during the 0-back task) among the whole sample ($P < 0.05$, FDR corrected at the voxel level).

*** Simple correlation coefficients between mean beta estimates of significant clusters and psychological scores. Note that due to overfitting in whole-brain analyses (Vul et al., 2009), the correlation coefficients of significant areas are overestimated to a degree

depending on the sample size and number of comparisons.

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Table 4. Brain regions showing significant interactions between originality/fluency scores and sex on brain activity.

Including gray matter areas*	x	y	z	TFCE score	Corrected P value (FWE, TFCE)	Cluster size (voxels)	activated/deactivated**	r*** (male/female)
Interaction between originality/fluency and sex on 0-back activity (positive effects in males and negative effects in females)								
Angular gyrus (B)/Calcarine Cortex (B)/Middle cingulum (B)/Posterior cingulum (B)/Cuneus (B)/Lingual gyrus (B)/Middle occipital lobe (B)/Superior occipital lobe (B)/Paracentral lobule (B)/ Superior parietal lobule (B)/Postcentral gyrus (B)/ Precuneus (B)/Rolandic operculum (B)/Middle temporal gyrus (L)/Superior temporal gyrus (L)/	-42	-57	27	652.04	0.0118	3100	589/2229	0.181/-0.085
Middle temporal gyrus (L)/Temporal pole (L)/	-45	6	-24	491.86	0.0348	129	33/53	0.085/-0.138
Hippocampus (L)/Parahippocampal gyrus (L)/	-27	-21	-24	490.78	0.0352	47	9/26	0.101/-0.107
Thalamus (L)/	-9	-18	0	483.07	0.0374	61	59/1	0.123/-0.077
Interaction between originality/fluency and activity of the contrast (2-back – 0-back) (positive effects in males and negative effects in females)								
Inferior parietal lobule (L)/Superior parietal lobule (L)/	-30	-57	39	488.67	0.0378	61	60/0	-0.143/0.126

*Labeling of the anatomical regions of gray matter is based on the WFU PickAtlas Tool

(<http://www.fmri.wfubmc.edu/cms/software#PickAtlas/>) (Maldjian et al., 2004; Maldjian et al., 2003) and the PickAtlas automated anatomical labeling atlas option (Tzourio-Mazoyer et al., 2002). In this atlas, temporal pole areas and some other areas include all subregions. Areas of the superior frontal other areas include areas of the superior frontal gyrus other than the medial, orbital, and medial-orbital parts of the superior frontal gyrus. Only areas with significant voxels comprising 10% or more of the cluster or areas with

50 or more significant voxels that existed in the cluster were reported.

**Percentage of voxels activated or deactivated during the corresponding condition (i.e., in the case of 0-back analyses, activity/deactivation during the 0-back task) among the whole sample ($P < 0.05$, FDR corrected at the voxel level).

*** Simple correlation coefficients between mean beta estimates of significant clusters and psychological scores. Note that due to overfitting in whole-brain analyses (Vul et al., 2009), the correlation coefficients of significant areas are overestimated to a degree depending on the sample size and number of comparisons.

Figure legends

Fig. 1. Distribution of the originality/fluency scores from the S-A creativity test in our sample.

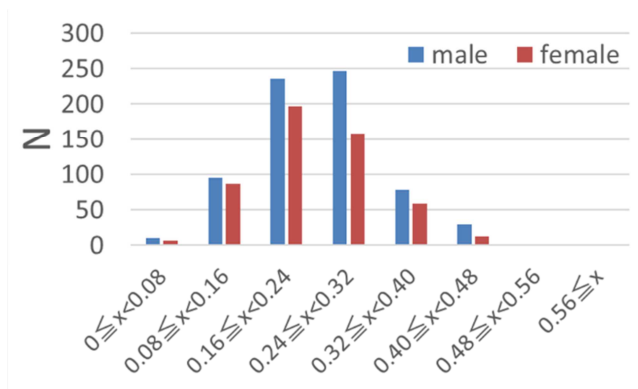
Fig. 2. Regions with a significant positive main effect of originality/fluency test score on the CMDT on brain activity. (Left panels) Originality/fluency score on the S-A creativity test showed a significant positive main effect on brain activity during the 0-back task (a), and that during the 2-back task (b) and activity of the contrast of 2-back – 0-back. Results were obtained using a threshold of $P < 0.05$, corrected for multiple comparisons based on 5000 permutations using TFCE scores. (Middle panels) Scatterplots of the associations between originality/fluency score on the S-A creativity test and mean beta estimates of significant clusters. (Right panels) Areas deactivated during the corresponding conditions. All results are displayed at a height threshold of 0.05, FDR corrected. (Left and right panels) Results are rendered on a “render” image or a “single-subject T1” image (in the case of section images) in SPM8.

Fig. 3. Regions with significant interaction effects between sex and scores on the CMDT on brain activity. (Left panels) Originality/fluency score on the S-A creativity test showed significant interaction effects with sex on brain activity during the 0-back task. This interaction was moderated by a positive correlation in males and negative correlation in females. Results were obtained using a threshold of $P < 0.05$, corrected for multiple comparisons based on 5000 permutations using TFCE scores. (Middle panels) Scatterplots of the associations between scores on the S-A creativity test and mean beta estimates of significant clusters. (Right panels) Areas activated (red) and deactivated (blue) during the corresponding conditions. All results are displayed at a height threshold of 0.05, FDR corrected. (Left and right panels) Results are rendered on

a “render” image or a “single-subject T1” image (in the case of section images) in SPM8.

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Figure 1.



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Figure 2.

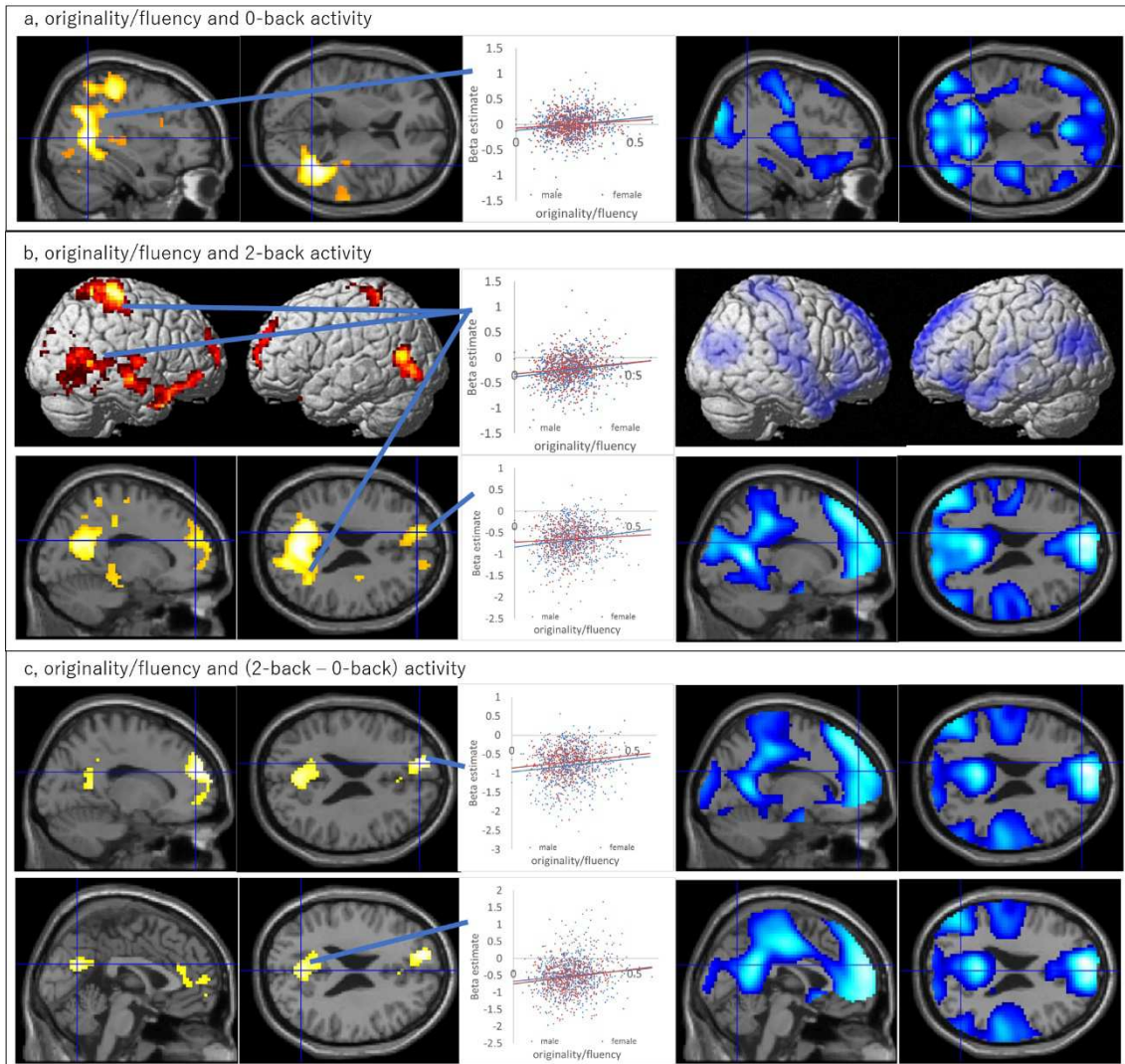


Figure 3.