Reliability of self-reported dispositional mindfulness scales and their association with working memory performance and functional connectivity

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Abstract

We systematically investigated the link between trait mindfulness scores and functional connectivity (FC) features or behavioral data, to emphasize the importance of the reliability of self-report mindfulness scores. Sixty healthy young male participants underwent two functional MRI runs with three mindfulness or mind-wandering task blocks with an N-back task (NBT) block. The data from 49 participants (age: 23.3 ± 2.8) for whom two sets of the self-reported Mindfulness Attention Awareness Scale (MAAS) and NBT performance were available were analyzed. We divided participants into two groups based on the consistency level of their MAAS scores (i.e., a "consistent" and an "inconsistent" group). Then, the association between the MAAS scores and FC features or NBT performance was investigated using linear regression analysis with *p*-value correction and bootstrapping. Meaningful associations (a) between MAAS and NBT accuracy (slope = 0.41, CI = [0.10, 0.73], corrected $p < 0.05$), (b) between MAAS and the FC edges in the frontoparietal network, and (c) between the FC edges and NBT performance were only observed in the consistent group ($n = 26$). Our findings demonstrate the importance of appropriate screening mechanisms for self-report-based dispositional mindfulness scores when trait mindfulness scores are combined with neuronal features and behavioral data.

Keywords: Functional connectivity; Functional magnetic resonance imaging; Mindfulness; Mindfulness attention awareness scale; N-back task; Working memory

1. Introduction

Mindfulness involves bringing one's attention to the present moment and recognizing the thoughts or feelings that come to mind without judging or evaluating them (Baer, 2003). Mindfulness can be categorized into trait mindfulness and state mindfulness based on the presence or absence of a dispositional characteristic and depending on whether it can be altered by mindfulness training interventions, respectively (Bauer et al., 2019; Giannandrea et al., 2019; Huang et al., 2021). Growing evidence shows that trait mindfulness is closely linked to functional states of the human brain such as attention and emotion regulation (Parkinson et al., 2019; Isham et al., 2020). For example, those with a higher dispositional mindfulness display a greater ability to discern emotional states (Teal et al., 2019) and show higher performance on working memory tasks based on increased attention levels (Jaiswal et al., 2018; Girardeau et al., 2020; Li et al., 2021).

Recently, a growing number of studies have investigated the neuronal underpinnings of trait mindfulness using functional neuroimaging modalities (Lim et al., 2018; Kaunhoven & Dorjee, 2021; Verdonk et al., 2021; Sezer et al., 2022). In a study utilizing a resting-state (RS) fMRI (Lim et al., 2018), a participant group with a high level of dispositional mindfulness showed enhanced (a) positive functional connectivity (FC) within the default mode network (DMN) and the salience network (SN), and (b) negative FC between the DMN and task-positive networks including the dorsal/ventral attention and executive control networks, compared to a group with low levels of dispositional mindfulness. Another study showed that levels of neuronal activation in the ventrolateral prefrontal areas were significantly reduced in adolescent participants with high dispositional mindfulness scores during an N-back task (NBT), possibly due to the low cognitive effort required to perform the task (Stein et al., 2022).

The investigation of the link between trait mindfulness and neural correlates of cognitive processes, such as working memory performance has paramount importance, for example to further develop mindfulness intervention techniques based on the underlying neural mechanisms. It is worth noting, however, that dispositional mindfulness scores are obtained based on self-reported questionnaires such as the Adult and Adolescent Mindfulness Scale (Droutman et al., 2018), the Five Facet Mindfulness Questionnaires (Baer et al., 2008), and the Mindfulness Attention Awareness Scale (MAAS) (Brown & Ryan, 2003). Such self-report-based evaluations of mindfulness scores can be easily falsified, particularly when participants do not respond reliably and/or truthfully. Therefore, we postulate that self-report scores of mindfulness need to be carefully screened before they can be entered into subsequent analyses.

In this study, we illustrate the importance of screening procedures for self-reported dispositional mindfulness scores when they are utilized to investigate the neural signatures of cognitive processes. To this end, we divided our recruited participants into two groups (one "consistent" and one "inconsistent" group) based on the level of reliability of their self-reported ratings across the two sets of trait mindfulness measured using the MAAS acquired within 3 weeks. The neural signatures of FC for the trait mindfulness scores were then compared between the two groups using fMRI data acquired while the participants performed a working memory NBT. The association between the trait mindfulness scores and the NBT performance was also compared between the two groups. We hypothesized that the association between scores and performance or FC features is more meaningful in those participants who had reliable self-reported trait mindfulness scores than in those who responded inconsistently/unreliably.

2. Method and Materials

2.1. Participants

The data presented in this study were collected within a randomized controlled trial that was registered at ClinicalTrials.gov (Identifier: NCT03148678; https://clinicaltrials.gov/ct2/show/NCT03148678). The institutional review board of our institute approved the study protocol, and all participants provided written informed consent. Inclusion criteria were right-handedness, no mental disorder, and no previous mindfulness experience based on verbal reports during telephone or face-to-face interviews. Subjects who met the inclusion criteria were enrolled for the smartphone-based ambulatory training and the MRI session (Fig. 1a). Sixty out of 70 recruited healthy males (age: 25.1 ± 2.9 years) completed the smartphone-based ambulatory training and the MRI session (Kim et al., 2019).

2.2. Experiment procedure

2.2.1. Smartphone-based ambulatory training

During the smartphone-based ambulatory training, participants who were naïve to mindfulness (MF) and mind-wandering (MW) strategies learned such strategies in an alternating order: they underwent 5 days of MF training and 5 days of MW training. The first training strategy was randomly chosen for each participant. The instruction for the MF training was, “Please pay attention to the physical sensation of your breath wherever you feel it most strongly in your body” (Brewer et al., 2011; Garrison et al., 2013; Meinlschmidt et al., 2016). The MW instruction was, “Please think about whatever comes to mind and go wherever your mind takes you” (Dickenson et al., 2013). More detailed information on the study protocol, including the smartphone-based ambulatory training sessions, has been reported elsewhere (Kim et al., 2019).

2.2.2. MRI session

Participants underwent an MRI session between 11 and 19 days after the first day of the ambulatory training session (Fig. S1). They completed two non-real-time fMRI runs during the MRI session, with each run consisting of three 3-minute blocks of either MF or MW strategy learning (labeled “MF run” and “MW run”). The session also contained one pseudo-randomly positioned 3-minute RS block. Moreover, participants completed three cognitive tasks following each MF or MW block, an emotion recognition task (Lee et al., 2013), an NBT (Smith & Jonides, 1997), and the Wisconsin Card Sorting Task (Grant & Berg, 1948), in counter-balanced order (Kim et al., 2019). We investigated the FC features of MF and MW associated with the dispositional MF scale using the MAAS and working memory performance using the NBT. Thus, we utilized the MAAS data collected during the face-to-face interviews and the MRI sessions as trait MF scores, and the fMRI data acquired during the NBT-based working memory task was used along with the behavioral data of the NBT (i.e., accuracy and response time [RT]).

2.3. Mindfulness Attention Awareness Scale (MAAS)

The MAAS is a self-report questionnaire used to assess levels of dispositional or trait MF rather than state MF (Brown & Ryan, 2003; Jeon et al., 2007). It consists of 15 items related to cognitive, emotional, physical, interpersonal, and general domains, and subjects are asked to respond based on their daily life experience (Lawlor et al., 2014). The higher the total score, the greater the level of dispositional/trait MF. Two sets of MAAS scores were collected from each participant within 3 weeks (Fig. S1). We hypothesized that the two sets of 15-item MAAS scores would be consistent if the participants responded reliably (Brown & Ryan, 2003).

2.4. N-back Task (NBT)

We employed a 3-back task consisting of letters (i.e., "a" to "z") to evaluate working memory performance (Smith & Jonides, 1997). Participants determined whether the current letter was the same as the letter that was shown three letters before in each trial. In our version of the task, a total of 85 trials followed the display of three training letters (Fig. 1b). Feedback (500 ms) and a cross-fixation (200 ms) period followed the stimulus in each trial. The feedback appeared immediately after the participants' button press in response to the stimulus; RTs thus varied within a 2-s range across trials (Fig. S2), which caused the inter-stimulus/trial intervals to jitter and thereby prevented potentially adverse repetition effects induced by fixed inter-trial/stimulus intervals.

2.5 MRI data acquisition and preprocessing

MRI data were acquired using a 3-T Siemens Tim-Trio scanner with a 12-channel head coil (Erlangen, Germany). A standard gradient-echo echo-planar-imaging (EPI) pulse sequence was used to measure blood-oxygenation-level-dependent (BOLD) contrasts (TR/TE = 1440/30 ms; flip angle = 71°; field of view = 192×192 mm^2; 50 axial slices without gap; slice thickness = 3 mm; in-plane matrix size = 64×64; voxel size = 3×3×3 mm^3) with a multiband factor of two and GeneRalized Autocalibrating Partial Parallel Acquisition (GRAPPA) acceleration. A 3D magnetization-prepared rapid gradient-echo (MPRAGE) pulse sequence was used to acquire the T1-weighted images (TR/TE = 1900/2.52 ms; flip angle = 9°; field of view = 256×256 mm^2; 176 sagittal slices without gap; voxel size = 1×1×1 mm^3). An MRI-compatible respiration belt and a fingertip pulse oximeter were used to acquire respiratory and cardiac-related signals during the fMRI session, respectively.

AFNI software was used for preprocessing. The preprocessing steps were applied using the *afni_proc.py* script in the following order: despiking using *3dDespike*, physiological noise correction using *@ANATICO*, alignment between anatomical T1 images and EPI images using *align_epi_anat.py*, spatial normalization to an MNI template, "MNI_avg152T1", using *@auto_tlrc*, head motion correction of EPI volumes to the base EPI volume using *3dvolreg* followed by registration of the motion-corrected EPI volumes into an MNI space using *3dAllineate*, spatial smoothing with an 8-mm full width at half maximum Gaussian kernel using *3dmerg*, in-brain mask definition using *3dAutomask*, detrending with polynomial functions using *3dDetrend*, scaling with a mean BOLD signal of 100 using *3dcalc*, and removing nuisance variables (i.e., six head motions and their derivatives) via regression. The respiration and pulse oximeter signals were used for additional physiological noise correction via RETROICOR (Glover et al., 2000), during which these potential confounding artifacts from physiological signals were removed from the BOLD signals (Kim et al., 2019).

2.6. Group classification based on the consistency of MAAS scores

We observed that the two sets of the MAAS scores obtained within a maximum 3-week period were not consistent for some of the participants, although the MAAS scores represent dispositional/trait MF which have been found to be reliable within 4 weeks (Brown & Ryan, 2003). Thus, we divided our participants into two groups based on the level of consistency/reliability between their two sets of 15-item MAAS scores. We used distances based on three different metrics (Pearson's correlation coefficient, cosine similarity, and Euclidean distances) to measure the consistency between two sets of MAAS scores obtained from the same participant during the face-to-face interview and the MRI session (Fig. 1a). We also employed several percentile thresholds (60^{th}, 70^{th}, 80^{th}, and 90^{th}) to define the boundary between consistent and inconsistent levels for each of the three metrics (Fig. S3) and thereby defined two groups of subjects whose MAAS ratings were consistent across all three measures (the consistent group) or inconsistent for any of the three measures (the inconsistent group).

One participant who had a maximum score for all 15 MAAS items during the pre-MRI session was excluded from the analysis. When the three types of distances to compare the two sets of MAAS scores were applied to the interquartile ranges (IQR) for outlier detection (i.e., 1.5×IQR above the upper quartile or below the lower quartile), three subjects met the outlier criteria for at least one of the three distances. In addition, the NBT performance of seven participants was lost due to a technical glitch. Thus, the data from a total of 49 males (age: 23.3 ± 2.8 years old) were entered into the analysis. We also collected demographic and psychometric information from participants as denoted in Fig. 1 (Kim et al., 2019). Potential differences between the consistent and inconsistent groups were evaluated using two-sample *t*-tests.

2.7. Behavioral data analysis

We analyzed the associations between the MAAS scores and the NBT performance for each of the two groups. The total sum of MAAS scores from (a) the interview day, (b) the MRI-session day, or (c) the average of both score sets were used, and two-sample *t*-tests were conducted to compare scores across groups. For the NBT, the accuracy (i.e., the percentage of correct trials among the total of 85 trials) and RT (i.e., the average RT of all correct trials) were calculated as performance measures for each MF and MW run. We then conducted a two-way mixed analysis of variance (ANOVA) to compare the accuracy and RT values from the NBT between the two groups and between the two conditions (i.e., MF or MW runs). We also calculated the difference in accuracy (ΔAccuracy = "Accuracy on MF run" – "Accuracy on MW run") and the difference in RT (ΔRT = "RT on MF run" – "RT on MW run") between the MF and MW runs. A linear regression was performed for the MAAS scores and (a) accuracy, (b) RT, (c) ΔAccuracy, or (d) ΔRT of the NBT, as well as a linear regression on accuracy and RT. We corrected *p*-values using random permutations (n = 10,000) and applied bootstrapping (n = 10,000) to obtain a confidence interval.

2.8. Functional connectivity (FC) analysis

The NBT block in each fMRI run was used for the FC analysis. We removed the global BOLD signal to get rid of a potential bias in the BOLD signal fluctuating across the whole brain (Power et al., 2017). The FC was calculated using Pearson's correlation coefficient (CC) *r* for the 360 region-of-interest (ROI) pairs (Glasser et al., 2016). Because of the short fixation period (200 ms) and since we expected that an NBT-based working memory function must be maintained throughout the block regardless of the correctness or incorrectness of trials, the BOLD signal from all trials was used for the FC calculation. The *r* values were normalized using Fisher's r-to-z and pseudo-z scores. Each of the ROIs was assigned to one of Yeo's seven functional networks (FN). We used the 44 ROIs belonging to the frontoparietal network (FPN), in light of previous reports that it is mainly associated with NBT performance (Lamichhane et al., 2020; Owen et al., 2005). The significant FC edges in the FPN that survived the corrected *p*-value threshold ($p < 10^{-5}$, FDR-correction) are reported for each MF/MW condition in each consistent/inconsistent group, along with the potential group difference.

2.9. Analysis using behavior data and FC

We performed a correlation analysis using (a) the FC values for each pair of the 44 ROIs in the FPN and (b) the accuracy/RT of the NBT or MAAS scores (i) for each (consistent and inconsistent) group and (ii) for both (MF and MW) conditions. When the accuracy or RT was obtained from the contrast between the MF and MW runs, the contrast of FC values between the MF and MW conditions was also obtained. We also performed a correlation analysis on the significant FC edges that survived our corrected *p*-value threshold and the MAAS scores to enhance reliability. The statistical significance of the correlations was corrected using 5,000 random permutations.

Moreover, we applied a mediation analysis framework to uncover the directional relationship between the trait mindfulness scales, working memory performance, and brain connectivity features. More specifically, we considered the functional connectivity features (i.e., FC edges) as the independent variable and either the N-back task working memory performance (i.e., accuracy and RT) or trait mindfulness scale data (i.e., from the MAAS) as the dependent variable and the remaining behavioral data as the mediator variable (Fig. S6). We conducted this mediation analysis for each FC edge of the FPN using all the participants in the consistent or inconsistent group and for each condition (MF and MW conditions). We report significant connections of direct (c') and indirect (ab) effects at the group level after p-value correction (corrected $p < 0.05$, bootstrapping with $n = 5,000$).

2.10. Estimation of whole brain activation patterns

We also assessed the whole brain activation patterns for the NBT to evaluate whether the task evoked-neuronal activations were associated with working memory processes. To this end, a general linear model was applied to each run (MF and MW), which contained regressors for the three MF or MW blocks, one RS block, one NBT blocks, an emotion recognition task block, and the Wisconsin Card Sorting Task block. It also included nuisance regressors for the six head motion parameters, and physiological noise correction based on aCompCor and RETROICOR (Kim et al., 2019). The resulting beta-valued maps of the NBT from the MF and MW runs for each subject were averaged, and a one-sample t-test was performed for each of the consistent/inconsistent groups using the average beta-valued maps across subjects (cluster-based correction using 3dClustSim with $p < 0.05$). The potential group difference was also evaluated using a two-sample t-test.

3. Results

3.1. Group definition based on two sets of MAAS scores

We selected the 70th percentile threshold for the distance measures to define the two groups with consistent or inconsistent 15-item MAAS ratings. This threshold (i.e., Pearson's distance = 0.42, Cosine distance = 0.40, and Euclidean distance = 0.54) provided a relatively more balanced number of participants per group (26 in the consistent group vs. 23 in the inconsistent group) compared to alternative threshold values (Fig. S3), which is a suitable approach for group comparisons. Demographic and psychometric details did not differ between the two groups (Table 1). The MAAS scores did also not differ between the two groups on the interview day (t-score = 0.991, p = 0.327); however, they differed on the MRI session day (t-score = 2.164, p = 0.036), 10 days after the ambulatory training (Table 2).

3.2. Behavior data analysis

Both the consistent and the inconsistent groups showed comparable performance on the NBT (accuracy [%]: 79.0 ± 10.2 for the MF run and 78.7 ± 11.9 for the MW run, consistent group; 78.9 ± 13.6 and 79.2 ± 12.5, inconsistent group; RT [s]: 0.88 ± 0.17 for the MF run and 0.89 ± 0.14 for the MW run, consistent group; 0.91 ± 0.17 and 0.88 ± 0.14, inconsistent group). For accuracy, there was no main effect of group (F[1, 47] = 0.003, p = 0.957, η_p^2 [effect size] = 0.00006), no main effect of condition (i.e., MF/MW) (F[1, 47] = 0.002, p = 0.964, η_p^2 = 0.00004), and no interaction (F[1, 47] = 0.109, p = 0.742, η_p^2 = 0.00232). For RT, there was no main effect of group (F[1, 47] = 0.065, p = 0.8, η_p^2 = 0.00138), no main effect of condition (F[1, 47] = 0.338, p = 0.564, η_p^2 = 0.00715), and no interaction (F[1, 47] = 0.744, p = 0.393, η_p^2 = 0.01559). Table 3 shows the number of correct NBT trials in each run and each group.

Figure 2 shows the significant positive correlation between the MAAS scores on the interview day and the difference in NBT accuracy (ΔAccuracy = "NBT accuracy on the MF run" – "NBT accuracy on the MW run") observed in the consistent group (slope = 0.41, *CI* = [0.10, 0.73], corrected $p < 0.05$; cf. slope = –0.04, *CI* = [–0.33, 0.23], corrected $p = 0.72$, inconsistent group). Neither group showed any significant relationship with ΔAccuracy when the MAAS scores were obtained on the MRI session day (slope = 0.19, *CI* = [–0.16, 0.53], corrected $p = 0.28$, consistent group; slope = 0.03, *CI* = [–0.29, 0.35], corrected $p = 0.86$, inconsistent group). When the two sets of MAAS scores were averaged, the trend was maintained (slope = 0.33, *CI* = [–0.02, 0.68], corrected $p = 0.06$, consistent group; slope = –0.02, *CI* = [-0.33, 0.29], corrected $p = 0.91$, inconsistent group). There were no significant associations between the MAAS scores and RT or ΔRT in either group (Table 4). The association between the accuracy and RT on the NBT showed a negative relationship between ΔAccuracy and ΔRT, but only in the consistent group (slope = –40.19, *CI* = [–61.33, –19.06], corrected $p < 0.001$, consistent group; slope = –0.88, *CI* = [–18.92, 17.17], corrected $p = 0.92$, inconsistent group) (Fig. S4).

3.3. Analysis using behavior data and FC

Figure 3a presents the FC edges within the FPN that were significantly associated with the MAAS scores in each of the MF and MW runs. Notably, the significant FC edges between the ROIs located in the frontal and parietal cortices were more substantial in the consistent than in the inconsistent group. The number of significant edges across all pairs of ROIs (labeled "Total" on the figure) and between the frontal and parietal regions ("F-P" on the figure) clearly show a greater number of edges in the consistent than in the inconsistent group (Fig. 3b). Figure S5a shows the significant FC edges for each of the MF/MW conditions in each group (consistent/inconsistent). Overall, we detected elevated positive FC edges in multiple subnetworks of the FPN, more so in the consistent than in the inconsistent group; however, our analysis did not reveal a statistically significant difference. Considering only these surviving FC edges, the positive association between the FC edges and the MAAS scores was also more evident in the consistent than in the inconsistent group (Fig. S5b).

Figure 4a illustrates the FC edges that showed a significant association between the difference in edges between the MF and MW runs (i.e., ΔFC = "FC edges in the MF run" – "FC edges in the MW run") and the difference in NBT accuracy (ΔAccuracy = "Accuracy on the MF run" – "Accuracy on the MW run"). Notably, the bilateral FC edges in the dorsolateral prefrontal cortex (dlPFC) showed a positive association in the consistent group. However, the bilateral FC levels in the dlPFC showed a negative association with the NBT accuracy in the inconsistent group. Figure 4b presents the edges that were shown significant associations between the difference in FC edges (i.e., ΔFC) and the difference in RT (i.e., ΔRT). The bilateral FC edges in the dlPFC showed a clear negative association with the RT on the NBT in the consistent group, while this association was less obvious in the inconsistent group.

Fig. S6a shows the significant FC edges for which the direct effect of the corresponding functional connectivity values and NBT performance (i.e., ACC) was significant in the mediation analysis using the MAAS scores as a mediator (top row). The substantial number of negative edges in the inconsistent compared to the consistent group indicates that the increased FC in the corresponding negative edges decreased NBT accuracy. The same pattern for significant negative edges stemming from the direct effect of functional connectivity on the NBT RTs observed in the comparison between the inconsistent and the consistent group suggests that the increased FC of the negative edges was associated with a decrease in RTs mainly in the inconsistent group. Figure S6b shows the direct effects of the FC and MAAS scores overall, revealing a greater number of positive edges in the consistent compared to the inconsistent group. We also observed a general decrease in the number of positive FC edges compared to the association between the FC and MAAS without NBT performance as a mediator. The number of negative edges in the inconsistent group was increased across the MF and MW conditions compared to the consistent group, indicating a positive association between FC and MAAS scores in the consistent rather than in the inconsistent group. We identified no significant indirect effect for any of the tested mediation models.

3.4. Whole-brain activation patterns

Figure 5 shows the whole-brain activation patterns for the NBT block in each group, revealing significant activations in the bilateral posterior region of the inferior frontal junction (IFJp) and medial intraparietal areas (MIP) in both groups. Voxel clusters did not differ significantly between groups (cluster-based correction using 3dClustSim with $p < 0.05$).

4. Discussion

4.1. Study summary

We investigated whether dispositional mindfulness levels are significantly associated with N-back working memory performance in participants naïve to meditation. To this end, we screened participants based on the reliability of their MAAS ratings acquired at two visits within 3 weeks. A strong association between MAAS scores and accuracy/RT on the N-back working memory task was found only in participants with consistent/reliable MAAS scores (i.e., the consistent group). However, there was no such meaningful association in the group with inconsistent/unreliable MAAS scores (i.e., the inconsistent group). We also identified substantial FC features in the FPN that were significantly associated with the MAAS scores between the frontal and parietal edges of the FPN, but only in the consistent group. The FC levels in the bilateral dlPFC of the FPN showed a strong positive association with NBT accuracy and a strong negative association with RT in the consistent group. However, these trends were found to be oppositive or less clear in the inconsistent group.

The significant association between the FC edges and behavioral data remained consistent overall when we controlled for potential indirect effects in the mediation analysis. More specifically, the association analysis for FC and NBT performance yielded substantially increased negative edges for the inconsistent compared to the consistent group, which may indicate mind-wandering-like behavior in the inconsistent group while participants were performing the NBT, even in the MF condition. This was not the case for the consistent group, where we observed a slightly increased number of negative edges in the MW compared to the MF condition. The positive association between FC and MAAS scores in the consistent group was reduced when we applied the mediation analysis; however, there were still a greater number of positive edges in the consistent compared to the inconsistent group and a greater number of negative edges in the inconsistent compared to the consistent group. This suggests a tight relationship between FC and behavioral data only in those subjects who performed consistently on the MAAS (i.e., the consistent group) but not in those who exhibited inconsistent behavioral performance across sessions. To the best of our knowledge, this is the first report that demonstrates that self-reported ratings of trait/dispositional mindfulness (i.e., MAAS scores) from meditation-naïve participants obtained during a research study need to be carefully screened for validity.

4.2. Mindfulness and N-back task-based working memory performance

We found that the difference in NBT accuracy between the MF and MW runs showed a significant positive correlation with the MAAS scores only in the consistent group. This indicates that participants whose trait mindfulness scores were high also showed higher NBT accuracy on the MF run than on the MW run, whereas participants whose trait mindfulness scores were low showed lower NBT accuracy on the MF run than on the MW run. On the other hand, there was no meaningful association between MAAS scores and NBT accuracy in participants in the inconsistent group, which demonstrates the importance of using reliable MAAS scores when corresponding mindfulness scores are used to analyze behavioral and/or brain imaging data. We believe that alternative trait mindfulness scales such as the Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006), the Kentucky Inventory of Mindfulness Scale (KIMS; Baer et al., 2004), and the Freiburg Mindfulness Inventory (FMI; Walach et al., 2006) can be similarly applied.

There were no significant associations between NBT accuracy and MAAS scores from either the MF or the MW run. This indicates that dispositional mindfulness levels are not directly associated with NBT performance per se (Noone & Hogan, 2018; Quickel et al., 2014; Stein et al., 2022). Instead, the improvement in NBT performance between conditions was associated with the dispositional mindfulness levels only in participants with consistent dispositional mindfulness levels. It is also worthwhile to note that RT on the NBT did not correlate with the MAAS scores.

4.3. Mindfulness levels and FC between the frontal and parietal lobe in the FPN

We found that the strength of the FC levels between the frontal and parietal regions in the FPN showed a substantial positive association with the MAAS scores when participants performed NBT working memory tasks, particularly in the consistent group on both MF and MW runs (Fig. 3). Previous studies reported that the mindfulness state is closely associated with a triple network (the default-mode network [DMN], central executive network [CEN], and salience network [SN]) (Bremer et al., 2022; Kim et al., 2019; Kim & Lee, 2022), of which the CEN includes the FPN. Investigation of the potential association between MAAS scores and the FC edges within the DMN or SN and between the three networks is warranted in future studies, for example with multivariate analysis frameworks such as a mediation analysis (Kim et al., 2019). The frontoparietal FC has been reported as an important biomarker for working memory performance in terms of attention maintenance and processes (Nyberg & Eriksson, 2016; Ptak, 2012). In the inconsistent group, some of the FC edges between the frontal and parietal ROIs were positively associated with the MAAS scores in the MF run. However, there was a dominant negative association between the FC edges and MAAS scores in the MW run, which indicated that the participants in the inconsistent group showed increased FC edges between the frontal and parietal ROIs when their mindfulness levels decreased (i.e., when their level of mind-wandering increased). These results were overall maintained when only the significant FC edges were considered for the association analysis using the MAAS scores.

4.4. N-back task performance and the dorsolateral prefrontal cortex

Previous studies reported that the dlPFC regions are the core brain regions for working memory performance on the NBT (Webler et al., 2022; Mencarelli et al., 2022; Balderston et al., 2017; Curtis & D'Esposito, 2003). We confirmed the role of the dlPFC regions (i.e., IFJp) and MIP in our whole-brain activation patterns in the NBT block for both groups (Fig. 5). We also found that NBT accuracy was positively correlated with the FC levels in the bilateral edges of the dlPFC in the consistent group (Fig. 4a). However, this association was negative in the inconsistent group, which suggests that the participants in this group might have been distracted by cognitive processes (i.e., mind-wandering). Conversely, the strong negative association between the FC levels in the bilateral dlPFC edges and RT was evident in the consistent group (Fig. 4b), whereas this association was compromised in the inconsistent group. Overall, the positive association between NBT accuracy and FC levels in the FPN edges and the negative association between NBT RT and the FC levels were both more clearly observed in the consistent than in the inconsistent group. This finding was also supported by the apparent negative association between ΔRT and ΔAccuracy only in the consistent group (Fig. S4).

4.5. Potential limitations and future directions

We used the 70th percentile threshold for each metric to measure dissimilarity between the two sets of 15-item MAAS scores and the subsequent analysis for group comparisons, since the threshold resulted in a relatively balanced number of subjects in both groups. We applied this threshold to all three similarity measures to select the participants who rated the two sets of the MAAS items consistently and thus had reliable MAAS scores. However, the choice of threshold might be somewhat arbitrary, and future research should thus be conducted to evaluate the reliability of our findings using a more rigorous threshold/criterion. Based on recent reports, trait mindfulness that is relatively stable compared to state mindfulness can be altered by mindfulness training interventions (Kiken et al., 2015). Thus, future studies are warranted to investigate the neural signatures of such altered state mindfulness and consequent changes in dispositional mindfulness, for example via intervention techniques.

Inter-stimulus/trial intervals were jittered in our NBT paradigm, owing to variances in RTs, which should have circumvented potentially adverse effects on BOLD signal parameter estimates induced by fixed interval event repetition (Ashby, 2019). The inter-stimulus/trial intervals in our NBT can be further optimized by using the "optseq" (https://surfer.nmr.mgh.harvard.edu/optseq/) or NeuroDesign (http://neuropowertools.org/design/start/) toolboxes to enhance the detection power of neuronal activations from rapid event-based trial designs.

We applied a FDR-based *p*-value correction when reporting the significant FC edges. Alternatively, network-based statistics can be applied, which is analogous to a cluster-based thresholding scheme for neuronal activation patterns and which was reported to be superior to a mass-univariate analysis controlled with FDR (Zalesky et al., 2010).

5. Conclusion

We found striking differences in (a) the link between the dispositional mindfulness scores and working memory performance and (b) the link between behavioral data and FC features from participants recruited for a research study. Dispositional mindfulness scores measured with the MAAS were strongly associated with N-back working memory task performance. The mindfulness scales and NBT performance had a strong association with the FC levels in the frontoparietal network, but only in those participants with reliable/consistent MAAS scores. We believe this is a very important point of our study that aimed to investigate potential associations between cognitive processes and dispositional/trait mindfulness scales. Our findings demonstrate the necessity of a proper screening mechanism to decide which participants can be included in a data analysis based on the reliability of multiple measurements of self-reported dispositional mindfulness scales.

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Figure Legends

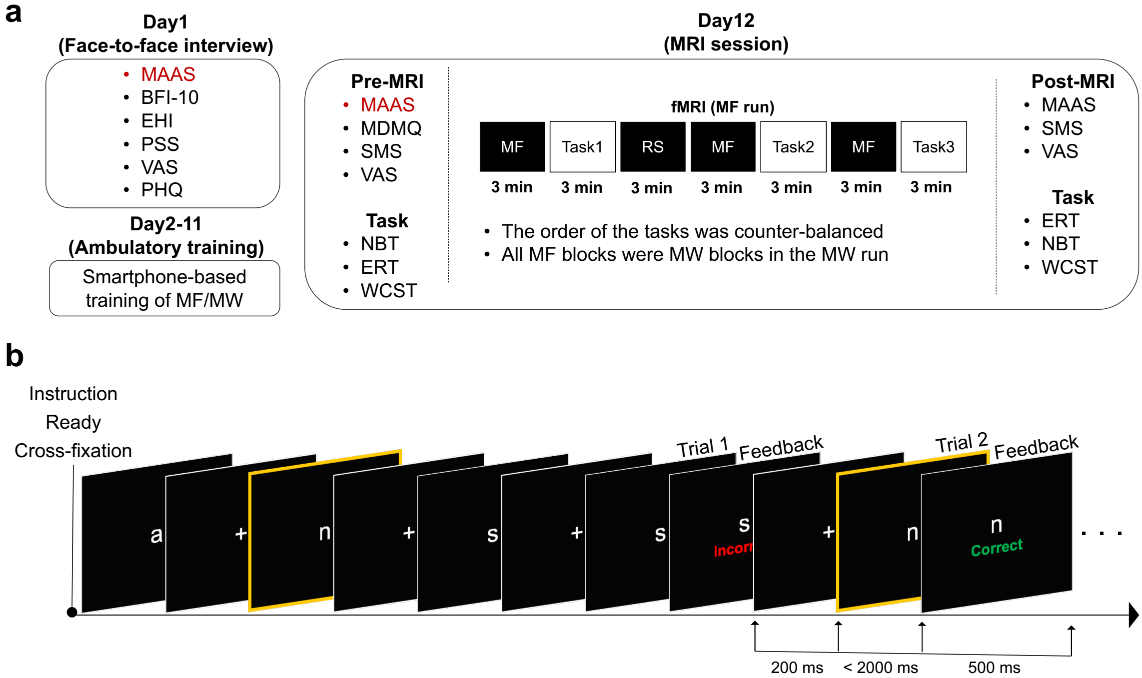

Figure 1. Overall study protocol and the adopted N-back task. (a) Study protocol. MAAS, Mindful Attention Awareness Scale; BFI-10, Big Five Inventory10; EHI, Edinburgh Handedness Inventory; PSS, Perceived Stress Scale; VAS, Visual Analog scale; PHQ, Patient Health Questionnaire; MDMQ, Multidimensional Mood State Questionnaire; SMS, State Mindfulness Scale; NBT, N-back task (here: 3-back task); ERT, emotion recognition task; WCST, Wisconsin Card Sorting Test; MF, mindfulness; MW, mind-wandering; RS, resting-state (b) N-back task paradigm. An instruction (1 s), a "ready" (1 s), and a cross-fixation (1 s) screen were displayed before the first letter. As feedback, the words "Incorrect" in red and "Correct" in green appeared after incorrect and correct trials, respectively.

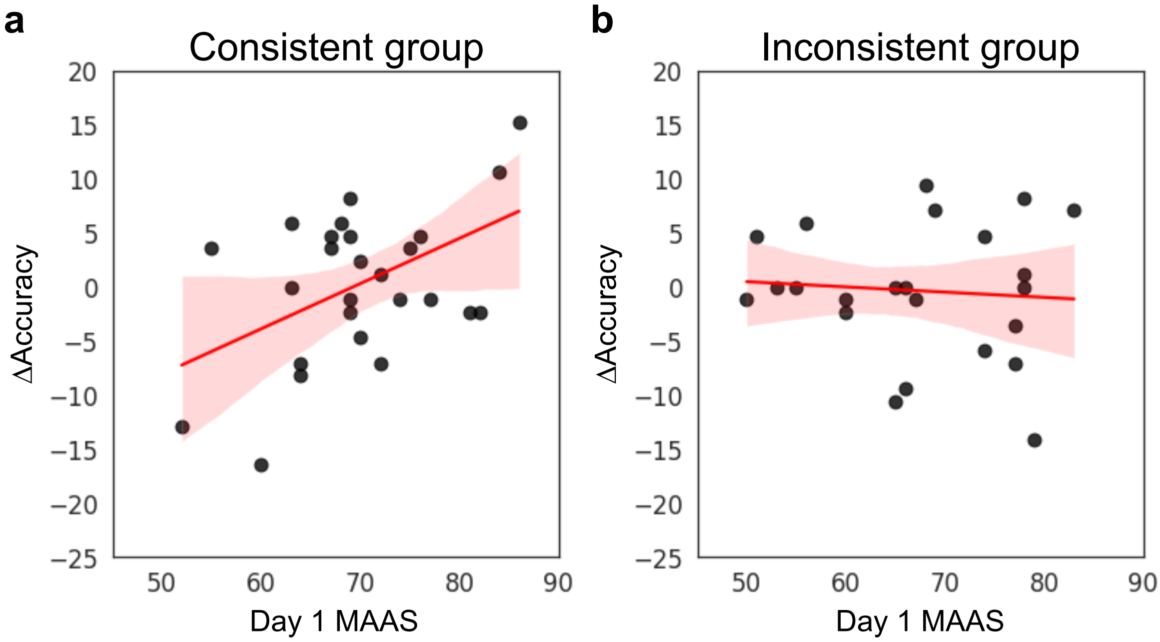

Figure 2. Regression on MAAS scores on the interview day (Day 1) and difference in NBT accuracy (i.e., ΔAccuracy = "Accuracy on MF run" – "Accuracy on MW run"). (a) The consistent group showed a significant positive relationship between MAAS scores and ΔAccuracy (slope = 0.41, *CI* = [0.10, 0.73] from 10,000-bootstrapping, $p < 0.05$, corrected using 10,000 random permutations). (b) The inconsistent group did not show a meaningful association between MAAS scores and the difference in accuracy (slope = –0.04, *CI* = [–0.33, 0.23], corrected $p = 0.72$).

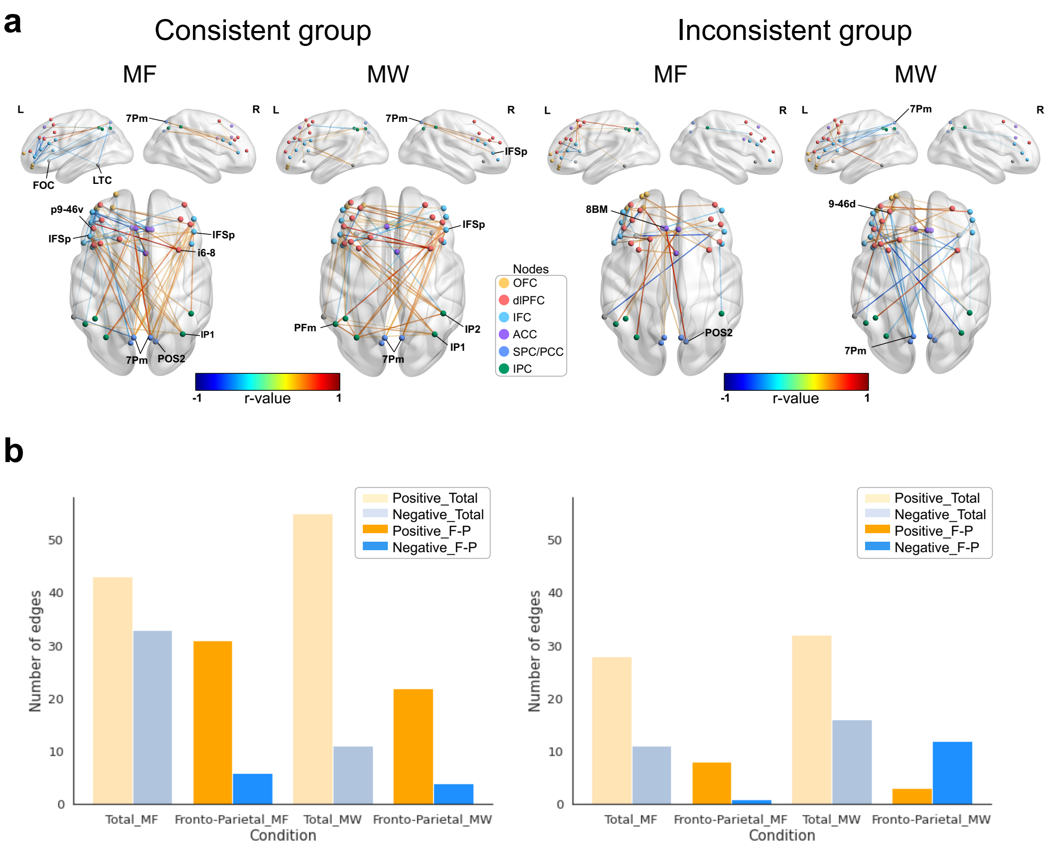

Figure 3. Association between MAAS scores and FC of the NBT block within the FPN network (corrected $p < 0.05$), with significant positive (orange) or negative (blue) correlations shown for each condition. (a) The consistent group (left) showed more positive edges for both the MF and MW runs than the inconsistent group (right). The representative nodes (i.e., the ROI in the FPN) are color-coded. (b) The number of significant edges in the consistent group (left) was greater than that in the inconsistent group (right). "Total_MF" and "Total_MW" are the numbers of significant edges across all pairs of ROIs in the FPN obtained from NBT_MF and NBT_MW, respectively. For "Fronto-Parietal_MF" and "Fronto-Parietal_MW", only the edges connecting the frontal and parietal regions in the FPN were counted. "Positive" and "Negative" denotes positive and negative edges, respectively. The frontal region included nodes located in the OFC, dlPFC, IFC, and ACC, while the parietal area included nodes located in the SPC, PCC, and IPC. OFC, orbital frontal cortex; dlPFC, dorsolateral prefrontal cortex; IFC, inferior frontal cortex; ACC, anterior cingulate cortex; SPC, superior parietal cortex; PCC, posterior cingulate cortex; IPC, inferior parietal cortex; ROI, region of interest

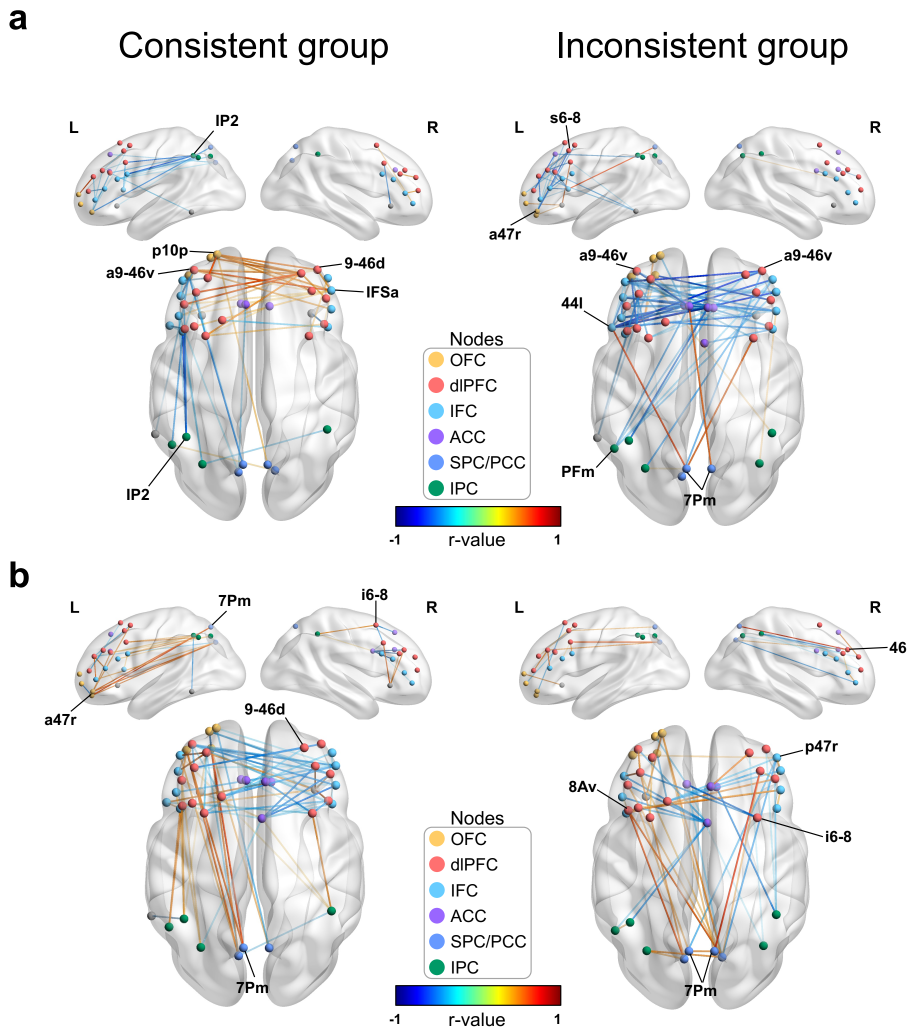

Figure 4. Association between NBT performance and FC of the NBT block within the FPN network (corrected $p < 0.05$). (a) A correlation analysis between the difference (i.e., "MF" – "MW") in accuracy (i.e., ΔAccuracy) and the difference in FC (i.e., ΔFC) was conducted and significant positive (orange) and negative (blue) edges are presented (corrected $p < 0.05$). The consistent group shows significant positive edges between the bilateral dlPFC (left), whereas the inconsistent group shows significant negative edges between the bilateral dlPFC (right). (b) A correlation analysis between the difference in RT (i.e., ΔRT) and the difference in FC (i.e., ΔFC) was conducted and significant edges are presented for the consistent (left) and inconsistent (right) group (corrected $p < 0.05$).

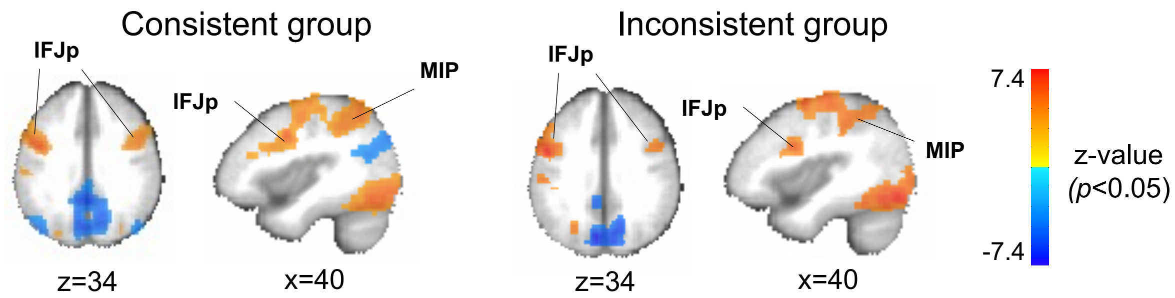

Figure 5. Whole-brain activation patterns in the NBT block at the group level (cluster-based correction using 3dClustSim with $p < 0.05$). IFJp, posterior region of inferior frontal junction; MIP, medial intraparietal area.