A Preliminary Neuroimaging Investigation of the Effects of Mindfulness Training on Attention Reorienting and Amygdala Reactivity to Emotional Faces in Adolescent and Adult Females

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Conflict of interest disclosure: Dr. Tamara Russell commercially provides mindfulness training programs (not the program included in this study) to adults and children.

Ethics approval: The study was approved by the University College London Research Ethics Committee, approval number 1602/003.

Patient consent: The parents or guardians of the adolescent participants and the adult participants provided signed informed consent, while adolescents verbally assented to taking part in the study and the pre- and post-training assessments.

Abstract

Introduction: Adolescence is a time of increased emotional reactivity and improving cognitive control. Mindfulness meditation training may foster adolescents' cognitive control and emotional regulation skills; however little is known about the impact of mindfulness training in adolescents compared to adults. We examined the effect of mindfulness meditation versus a closely matched active control condition (relaxation training) on behavioural and neural measures of cognitive control and emotional reactivity in a small group of adolescents and adults.

Methods: Structural and functional magnetic resonance imaging data were collected before and after 8 weeks of training in 26 adolescent (12-14 years) and 17 adult (23-33 years) female participants in the UK while they completed an *n*-back task with emotional face distractors and an attentional control task. Participants of each group chose a class date/time and the classes were then randomly allocated to mindfulness or relaxation conditions.

Results: Compared to relaxation training, mindfulness training led to an increase in the speed of reorienting attention across age groups. In addition, there was preliminary evidence for reduced amygdala response to emotional face distractors in adolescents after mindfulness training.

Conclusions: An 8-week mindfulness program showed similar facilitative effects in adolescent and adult females on the reorienting of attention, a skill that is repeatedly practiced during mindfulness meditation. Mindfulness also reduced left amygdala reactivity to emotional face distractors in adolescents only. Mindfulness meditation practice can therefore have a facilitative effect on female adolescents' attentional control, and possibly attenuate their emotional reactivity.

Keywords: mindfulness, cognitive control, emotional reactivity, neuroimaging, development

A Preliminary Neuroimaging Investigation of the Effects of Mindfulness Training on Attention Reorienting and Amygdala Reactivity to Emotional Faces in Adolescence and Adulthood

Mindfulness-meditation training (MT) programs have been found to improve aspects of cognitive control and emotion regulation in adults (Eberth & Sedlmeier, 2012; Gallant, 2016) and to be associated with structural (Tang et al., 2010) and functional brain changes (e.g. Allen et al., 2012; Farb et al., 2010; Kral et al., 2018; Moore et al., 2012; Slagter et al., 2007). These findings have led to interest in using MT with youth (Greenberg & Harris, 2012; Sanger & Dorjee, 2015; Tan, 2016; Zelazo & Lyons, 2012). There are now several programs specifically designed to teach mindfulness to adolescents (e.g., Biegel et al., 2009; Broderick & Frank, 2014), including on a large scale in schools (Kuyken et al., 2022). MT appears to have beneficial effects on behavioural and neural aspects of attention in adolescence, though the specific aspects that are improved differ by study (Baijal et al., 2011; Bauer et al., 2020; Bögels et al., 2008; Felver et al., 2017; Leonard et al., 2013; Sanger et al., 2018; Sanger & Dorjee, 2016). With regard to emotion regulation, self-report data suggest increased positive affect and emotion regulation after MT in adolescents (e.g. Bauer et al., 2019; Biegel et al., 2009; Broderick & Metz, 2009; Coholic et al., 2012; Klingbeil et al., 2017; Kuyken et al., 2013; Metz et al., 2013). However, other studies do not find benefits of mindfulness training in adolescence (Dunning et al., 2022a; Kuyken et al., 2022; see Dunning et al., 2022b for a recent meta-analysis).

Because cognitive control and emotion regulation continue to mature during adolescence (Blakemore, 2008; Crone & Dahl, 2012; Luna et al., 2010; Tottenham & Gabard-Durnam, 2017), and adolescence is thought to be associated with greater emotional reactivity (Guyer et al., 2008; Hare et al., 2008), adolescents may benefit more from MT than adults. Alternatively, MT may be relatively more effective in adults, because adults may be more capable of engaging in the kinds of sustained attentional control required to benefit fully from MT. The current experiment was designed to address these alternatives while examining specific effects of mindfulness training versus a well-matched active control condition using both behavioural and neural measures. This brief report summarises key findings of this study.[1]

Method

Participants

We chose to focus only on female participants because the socio-emotional disorders associated with emotional dysregulation that emerge during adolescence predominantly affect females (Rapee et al., 2019). Fifty-one female participants (28 adolescents, 23 adults) with no history of a developmental or mental-health disorders and with no previous training in mindfulness or meditation participated in this study and were told they would take part in a stress-reduction intervention. The sample with complete data is described in **Table 1.** Participants completed the verbal subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) at T2 and groups were matched in age and general cognitive abilities (**Table 1**). The study was approved by the University College London Research Ethics Committee.

INSERT TABLE 1 HERE

Training Intervention

Participants were randomised to MT or a Relaxation Training (RT) active control condition that was designed to control for potential effects of MT (e.g., relaxation and expectation of benefits) that are not specific to MT (Eberth & Sedlmeier, 2012; Jain et al., 2007; Ortner et al., 2007). Randomisation was achieved by offering two class times for each age group (Saturdays 1.30

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[1] A full report is provided as an attachment to this submission and will be uploaded on an online repository pending acceptance of this manuscript to preserve anonymity of the peer review process.

pm or 3.30 pm for adults, Wednesdays or Thursday 4 pm for adolescents), having participants select a time slot, and then randomly allocating the training time to RT or MT.

The mindfulness group completed the *Learning to Breathe* program (Broderick, 2013), and the relaxation group completed a course developed for this study that taught a variety of relaxation techniques and skills and was closely matched in terms of class length, number of activities, and home practice. The same instructor, a clinical psychologist and experienced Mindfulness Trainer, led both courses, ensuring the training conditions were equated for teacher qualities. Both conditions were expected to produce beneficial effects, but only mindfulness was predicted to facilitate the reorienting of attention that is central to mindfulness training (Wielgosz et al., 2019).

Participants attended 8 weekly 90-minute lessons. During each class participants practiced mindfulness or relaxation exercises and then participated in a teacher-led discussion of their experiences. Participants also completed daily home exercises with audio recordings and a workbook.

Measures

Participants completed both an attentional control task and an emotional *n*-back task in a magnetic resonance imaging (MRI) scanner. Questionnaires and a verbal working memory task were completed outside the scanner and are described in the full report (https://osf.io/fx96m/). Stimulus presentation was programmed in Cogent (www.vislab.ucl.ac.uk/Cogent/index.html) running in Matlab 7.11 (MathWorks).

Attentional control task. Participants completed a variant of the Attention Network Test (Fan et al., 2002) designed to require participants to *reorient* their attention on 20% of trials when a spatial cue was invalid (Konrad et al., 2005), to match the attentional skill practiced during mindfulness meditation more closely than the standard *alerting* and *orienting* measures. The task used in the present study included two factors: target congruency (congruent or incongruent flankers) and cue validity (valid or invalid cues) in an event-related design (**Fig. 1A**). After practice, participants performed two runs of the task, each including 150 trials and 33 null events. The four trial types were presented in a counterbalanced order fixed for all participants.

INSERT FIG. 1 HERE

Emotional n-back task. Participants completed an emotional *n*-back task (adapted from Ladouceur et al., 2009) to measure resistance to emotional interference. Trials were presented in a 2 (Task: 0-back, 2-back) x 3 (Distractors: no distractors, fearful faces, happy faces) blocked factorial design. Participants were shown single digit numbers presented centrally; in addition, in the distractor conditions, two identical faces were presented on either side of the number (**Fig. 1B**). After practice, participants completed two or three scanning runs of the task, each including three repeats of each of the six block types and four fixation blocks, lasting 18.8 s. Task blocks were preceded by 1.2 s of instructions indicating to participants which task they were going to perform next.

MRI Data Acquisition. A 1.5-T MRI scanner with a 30-channel head coil (Siemens TIM Avanto, Erlangen, Germany) was used to acquire multislice T2-weighted echo-planar volumes with blood-oxygen-level dependent (BOLD) contrast. Functional imaging data runs took 6-7 min, and a T1-weighted structural image lasting 5 min 30 s was acquired between the two tasks (see full report (https://osf.io/fx96m/) for details of the scanning sequences).

Data Analyses

This report focuses on analyses of training practice and specific effects of MT training revealed by time by condition interactions. Additional analyses can be found in the full report (https://osf.io/fx96m/).

Behavioural data. No outliers were identified. Analyses were carried out using SPSS 26 (IBM Corp., Armonk, NY) using mixed repeated measures analyses of variance (rmANOVAs). In the emotional *n*-back task the happy and fearful faces conditions were combined to simplify the analyses and the complexity of possible interactions, considering the small sample size.

MRI data. Functional imaging data were preprocessed and analysed using SPM8 (Statistical Parametric Mapping, Wellcome Trust Centre for Neuroimaging, http://www.fil.ion.ucl.ac.uk/spm/). Scanning runs were modelled by a set of event-related (attentional control task) or boxcar (emotional n-back task) regressors in the general linear models (GLM). Two approaches were taken. First, whole-brain analyses were run using family wise error (FWE) correction at the cluster level (see full report https://osf.io/fx96m/ for contrast images of the task main effects). Second, Neurosynth (neurosynth.org) was used to independently define regions of interest (ROI) for analysis of training effects running meta-analyses with the search terms "attention," for the attentional control task, and "emotional faces" and "updating" for the emotional n-back task. Clusters larger than 700 mm^3 were included in the analyses (**Fig. 2**). Mean parameter estimates were extracted using MarsBar (Brett et al., 2002). Voxel-based morphometry (VBM) (Kurth et al., 2015) was used to analyse changes in brain structure over the course of training. For full description of the functional and structural analyses steps, as well as the structural analyses results, please refer to the full report (https://osf.io/fx96m/).

INSERT FIG. 2 HERE

Results

Practice

Attendance rates were higher for adolescents than adults but did not differ as a function of training condition. Number of home practice sessions was estimated from the activity workbooks.[2] While age groups did not differ in number of practice sessions, an interaction between age group and training revealed that adolescents practised more in the mindfulness than the relaxation condition, while adults did not (see full report for statistical analyses, https://osf.io/fx96m/).

Attentional Control Task

Time (T1, T2) x Age group (adolescents, adults) x Training condition (mindfulness, relaxation) x Target congruency (congruent, incongruent) x Cue validity (valid, invalid) mixed rmANOVAs were performed on percentage accuracy and mean reaction time for correct trials. The only significant ($p < .05$) interaction involving time and condition was a Time x Training condition x Cue validity interaction, $F(1,39) = 8.77$, $p = .005$, $\eta_p^2 = .184$ in the reaction time data (**Fig. 3a, 3b**). Estimation statistics (https://www.estimationstats.com/) were used to follow-up this effect of interest (Ho et al., 2019). Paired-comparisons indicated that the cost on reaction time of cue validity (difference in reaction time between invalid and valid cues) significantly decreased over time in the mindfulness group, paired Cohen's $d = -0.571$, 95.0% CI [-0.909, -0.273], Wilcoxon test $p < .001$, but not in the relaxation group, $d = 0.0731$, [-0.225, 0.319], $p = .465$ (**Fig. 3c, 3d**). Age group did not further modulate this interaction, suggesting similar effects in adolescents and adults. The invalid vs. valid cue difference decreased between T1 and T2 in the adolescent (-18 ms, 95.0% CI [-33, -3]) and adult (-25 ms, [-44, -6]) MT groups, whereas it increased in the adolescent

[2] Some of these data were missing as not all participants returned the workbooks after testing.

(+5 ms, [-10, 20]) and adult (+1 ms [-18, 19]) RT groups. Neither whole-brain analyses nor ROI analyses revealed significant interactions with time and training condition.

INSERT FIG. 3 HERE

Emotional N-Back Task

Time (T1, T2) x Age group (adolescents, adults) x Training condition (mindfulness, relaxation) x Task (0-back, 2-back) x Distractors (blank, emotional faces) mixed rmANOVAs were performed on the percentage accuracy and mean reaction time for correct trials data. There were no specific effects of mindfulness training on this behavioural measure of resistance to emotional interference. Again, the whole-brain analyses did not reveal significant interactions with time and training condition.

Analyses of the ROI data, however, showed a Time x Distractors x Training intervention x Age group interaction, $F(1,39) = 5.70$, $p = .022$, $\eta_p^2 = .461$, in the left amygdala cluster derived from the “emotional faces” search term (**Fig. 4a**). There were opposite patterns of Time x Distractors x Training intervention interactions in the two age groups, although neither reached significance (adolescents: $F(1,24) = 3.62$, $p = .069$, $\eta_p^2 = .131$, adults: $F(1,15) = 2.32$, $p = .148$, $\eta_p^2 = .134$). Post-hoc paired t-tests comparing the difference in mean parameter estimate between emotional faces and blank conditions in the left amygdala at T1 and T2 indicated a significant decrease in activation in response to faces in the adolescent MT group only, $t(12) = 2.19$, $p = .049$, other p’s > .18 (**Fig. 4b**). Similarly, the middle frontal gyrus cluster identified with the “updating” search term (**Fig. 4c**) showed a Time x Distractors x Training intervention interaction, $F(1,39) = 4.33$, $p = .044$, $\eta_p^2 = .100$. The pattern was that of a decrease in the difference between emotional faces and blank condition between T1 and T2 in MT and an increase in RT, but these changes were not significant (mindfulness: $F(1,19) = 2.72$, $p = .116$; relaxation: $F(1,20) = 1.58$, $p = .223$) (**Fig. 4d**).

INSERT FIG. 4 HERE

Discussion

The results of this study demonstrate that in female participants mindfulness training improved a specific aspect of attentional control, reorienting of attention, which is practiced repeatedly during mindfulness meditation. The cost on reaction time of cue validity decreased over time in the mindfulness group only. In adolescents only, these specific effects of mindfulness on reorienting were accompanied by a significant decrease in left-amygdala activation in response to emotional faces. This finding provides preliminary evidence that mindfulness meditation practice has broader impacts for female adolescents than for adults. Failures to regulate emotions are associated with a wide range of developmental difficulties during adolescence, including the emergence of psychopathologies, such as mood disorders (Rapee et al., 2019). The results reinforce previous research findings showing that mindfulness meditation training can be a tool to foster better attentional control and emotion regulation during adolescence, when emotion regulation is particularly challenging (Ahmed et al., 2015; Crone & Dahl, 2012). Of note, these findings were observed using a well-matched relaxation training active control condition, which set a rigorous bar for assessing impacts of MT by controlling for training effects not specific to mindfulness (Eberth & Sedlmeier, 2012; MacCoon et al., 2012), suggesting that the particular acts of focusing one’s attention in a non-judgmental way on one’s moment to moment experiences may be particularly beneficial for adolescent emotional and cognitive development, at least in females.

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Tables

Table 1

Descriptive Statistics of Participant Demographics and Attendance and Estimated Practice Data for the Mindfulness Meditation Training (MT) and Relaxation Training (RT) Conditions

Age group	**Adolescents**		**Adults**		**Statistics**
Training condition	**MT**	**RT**	**MT**	**RT**	
N	13	13	8	9	
Age (years) ***M* (*SD*)**	13.6 (0.5)	13.9 (0.7)	28.7 (3.7)	27.9 (2.7)	MT vs. RT adolescents: $t(24) = 1.42$, $p = .168$ MT vs. RT adults: $t(24) = 0.61$, $p = .612$
Verbal IQ ***M* (*SD*)**	117.3 (8.2)	118.0 (6.3)	118.2 (7.2)	119.7 (5.9)[a]	Training condition, $F(1,38) = 0.238$, $p = .628$, $\eta_p^2 = .006$ Age group, $F(1,38) = 0.327$, $p = .571$, $\eta_p^2 = .009$ Condition x Age group, $F(1,38) = 0.032$, $p = .858$, $\eta_p^2 = .001$

[a] WASI data missing for one participant in this group.

Figure captions

Fig. 1 Experimental paradigms. (**a**) Attentional control task. Presented here are the timings of a single trial of the task. A central fixation cross appeared throughout. The spatial cue (asterisk) appeared above or below the fixation cross and was either valid (predicted the target location, 80% of the trials) or invalid (opposite location, 20% of the trials). The target stimulus consisted of five arrows oriented in congruent (50% of the trials) or incongruent (50% of the trials) directions; it appeared above or below the fixation cross. The interstimulus interval (ISI) was jittered. (**b**) Emotional n-back task. On the left is shown an example series of trials for the no distractor (blank) 0-back condition, where participants were asked whether the number was zero. On the right is shown an example series of trials for the happy distractors 2-back condition, where participants were asked whether the number was the same number as two trials before. As a reminder to participants, the central fixation cross was surrounded by a small black circle in 0-back blocks. Emotional face stimuli from 72 identities (half males, half females), cropped to an oval and converted to greyscale, came from the NimStim database (Tottenham et al., 2009), the NIMH Child Emotional Faces Picture Set (Egger et al., 2011) and the Karolinska Directed Emotional Faces (KDEF) set (Lundqvist et al., 1998). A mixture of adults, young adults and adolescent faces were used. Note the scale of the stimuli was modified for clarity.

Fig. 2 The largest clusters obtained from Neurosynth search of the terms “attention,” “emotional faces” and “updating” are plotted on a brain template using MarsBar in Statistical Parametric Mapping (SPM) 12. The search term “working memory” was investigated but was associated with a too large number of regions to provide a useful set of regions of interest. (**a**) Six clusters positively associated with the search term “attention.” These were located in the left hemisphere in the superior parietal gyrus, extending into inferior parietal gyrus (143 voxels centred on -24 -58 52), middle frontal gyrus, extending into superior frontal and precentral gyri (64 voxels centred on -27 -4 51) and middle occipital gyrus, extending into inferior occipital gyrus (30 voxels centred on -44 -69 -1) and in the right hemisphere in the superior occipital and superior parietal gyri, extending into the middle occipital gyus (281 voxels centred on 24 -65 46), the right precentral, middle frontal and superior frontal gyri (161 voxels centred on 35 1 47) and inferior parietal gyrus (39 voxels centred on 42 -45 48). (**b**) Four clusters positively associated with the search term "emotional faces" and were located in the left (157 voxels centred on -23 -3 -18) and right amygdalae (161 voxels centred on 28 -1 -18), and the left (28 voxels centred on -39 -52 -12) and right fusiform gyri (41 voxels centred on 41 -41 -18). (**c**) The search term "updating" was associated with a single cluster in the superior part of the middle frontal gyrus (38 voxels centred on 27 13 48).

Fig. 3 Mindfulness training, but not relaxation training, led to a reduction in the cost on reaction time of cue validity in the attentional control task. **(a)** Reaction time as a function of training condition (mindfulness/relaxation), cue validity and time. There was a significant three-way interaction suggesting that participants in the mindfulness training condition improved more on invalid cue trials over time than participants in the relaxation training condition. Error bars represent estimated *SE.* (**b**) Combined violin and boxplot of the difference in reaction time between invalid cue trials, which require reorienting of attention, and valid cue trials, is plotted as a function of Time (T1, T2) and training condition. Mean and errors bars are estimates from the ANOVA. (**c**) The raw differences in reaction time are plotted as a function of time and training condition; each paired set of observations is connected by a line. (**d**) Effect sizes (paired Cohen's *d*) are shown in a Cumming estimation plot. Each paired mean difference is plotted as a bootstrap sampling distribution. Mean differences are depicted as dots; errors bars represent 95% confidence intervals. * $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$.

Fig. 4 Regions of interest (ROIs) analyses results in the emotional n-back task. In the left amygdala ROI, identified using the search term "emotional faces," there was a significant Time x Distractors x Training condition x Age group interaction, which suggested that adolescents showed a decrease in amygdala response to emotional face distractors after mindfulness training. (**a**) Overlay of the left amygdala ROI. (**b**) Plot of the mean parameter estimate of the difference between emotional faces and blank conditions in the left amygdala as a function of age group, training condition and time. In the right superior middle frontal gyrus ROI identified using the search term "updating" there was a significant Time x Distractors x Training condition interaction, with a reduction of the response to emotional face distractors across age groups between T1 and T2 in the mindfulness group, but follow-up comparisons were not significant. (**c**) Overlay of the right superior middle frontal gyrus ROI. (**d**) Plot of the mean parameter estimate of the difference between emotional faces and blank conditions in the right frontal ROI as a function of training condition and time. † < $p < .1$, * $p < .05$.

Figures

Fig. 1

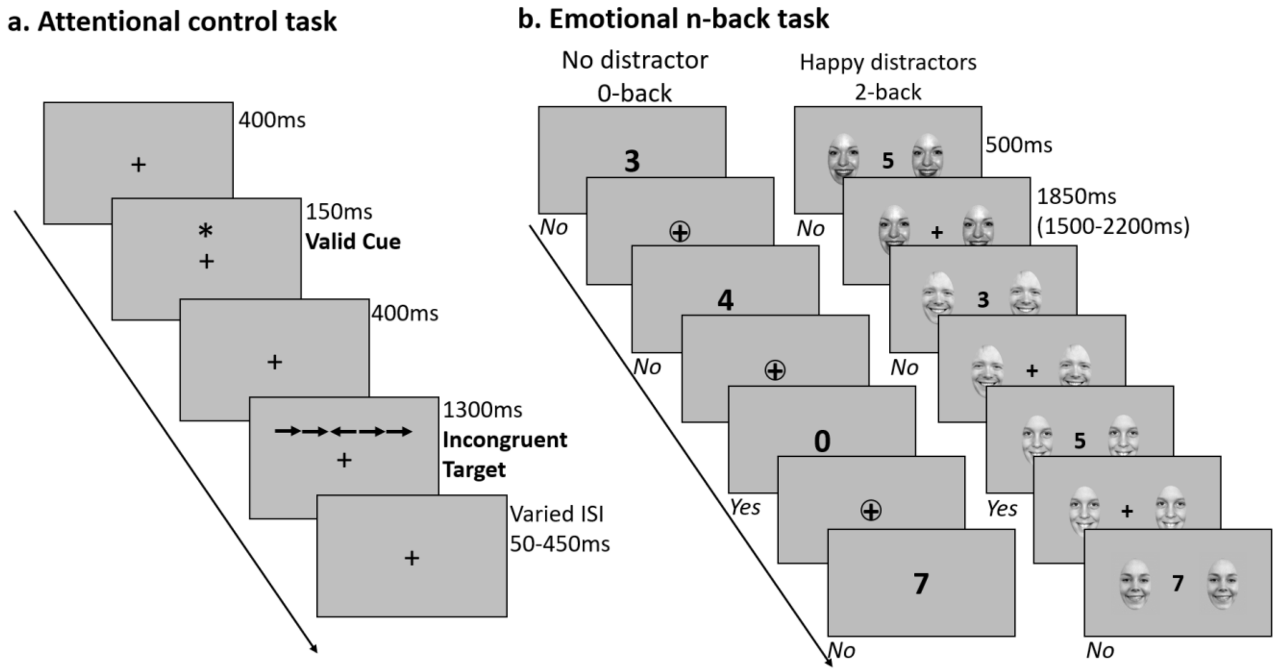


Fig. 2

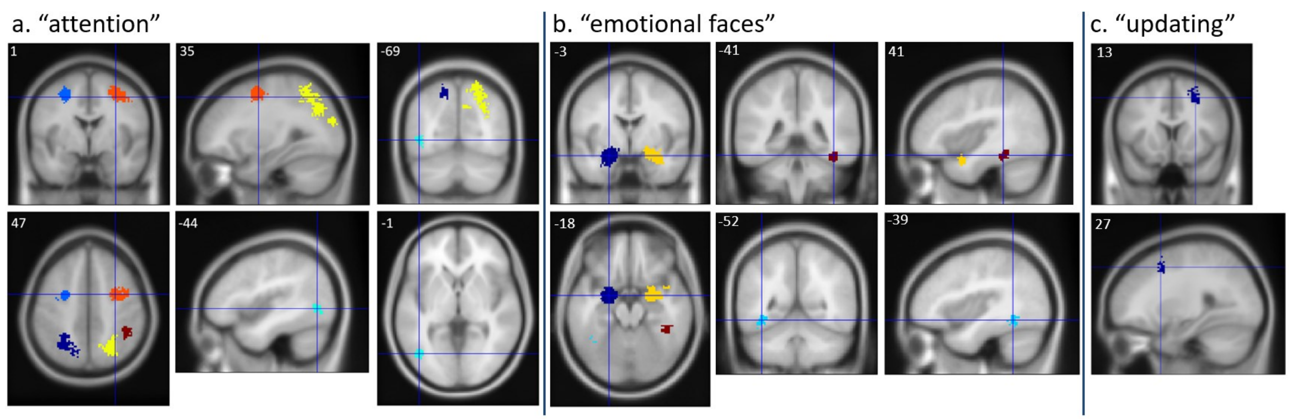


Fig. 3

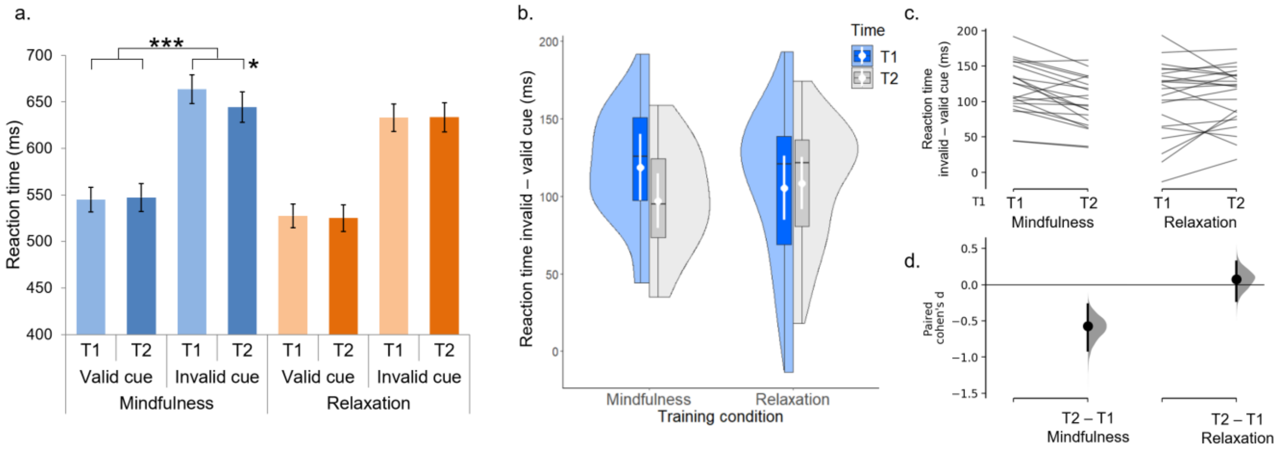
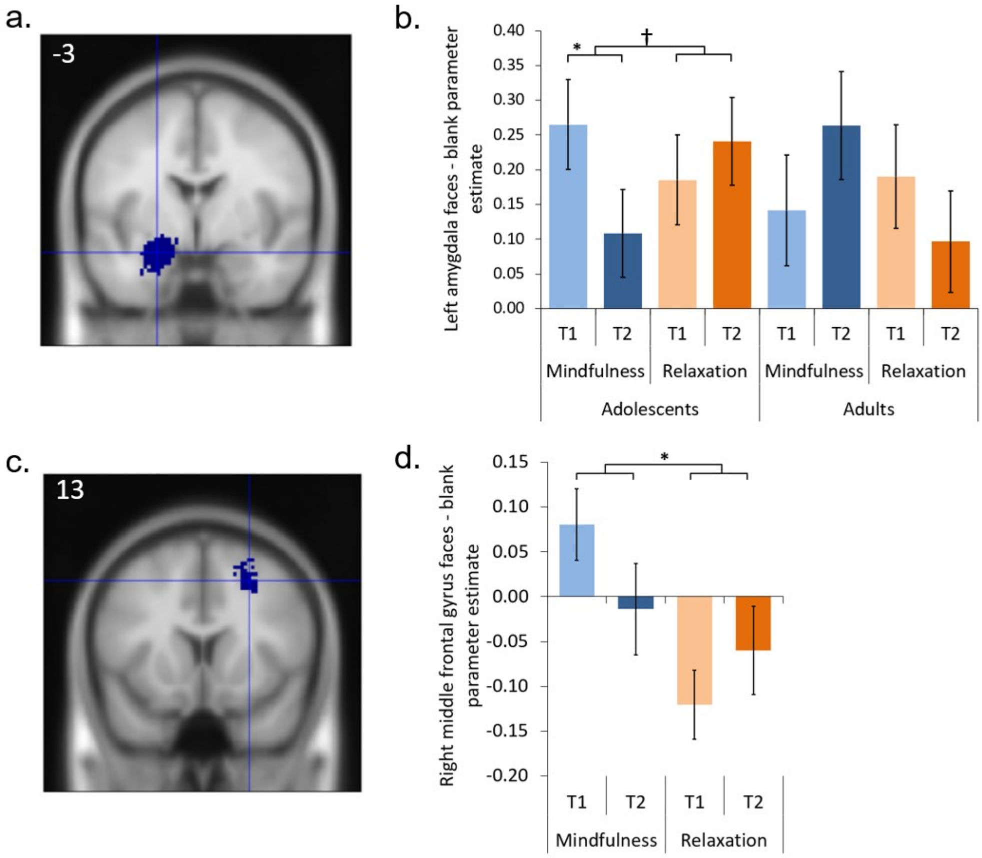

a.
Reaction time (ms)
700
650
600
550
500
450
400
***
*
T1
T2
Valid cue
Invalid cue
Mindfulness
Relaxation
b.
Reaction time invalid – valid cue (ms)
Time
T1
T2
Mindfulness
Relaxation
Training condition
c.
Reaction time invalid – valid cue (ms)
Mindfulness
Relaxation
d.
Paired cohen's d
T2 – T1
Mindfulness
T2 – T1
Relaxation

Fig. 4


a.
-3
b.
Left amygdala faces - blank parameter estimate
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
*
†
T1
T2
Mindfulness
Relaxation
Adolescents
Adults
c.
13
d.
Right middle frontal gyrus faces - blank parameter estimate
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
*
T1
T2
Mindfulness
Relaxation