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Research paper

Mindfulness training with adolescents enhances metacognition and the inhibition of irrelevant stimuli: Evidence from event-related brain potentials

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ABSTRACT

With the increased interest in school-based mindfulness interventions, there have been repeated calls to investigate neurodevelopmental markers of change. This non-randomised study of 16–18 year olds with wait-list control group examined possible enhancements to brain indexes of attention processing after school-based mindfulness training using event-related potentials (ERPs) ($N=47$ for self-report; $N=40$ for ERPs). Results showed significantly more negative N2 amplitudes after training, in response to irrelevant frequent stimuli and colour-deviant non-target oddball stimuli in a visual oddball paradigm. Improvements in negative thought controllability were associated with more negative N2 amplitudes post-training across groups, and mindfulness training was associated with reductions in students' hypercritical self-beliefs. There were no group differences on task performance, but regression analysis indicated that programme satisfaction explained 16% of the variance in improved target accuracy. Together these results suggest that a school-based mindfulness curriculum can enhance older adolescents' task-relevant inhibitory control of attention and perceived mental competency.

1. Introduction

Mindfulness interventions involve guided training of present-moment awareness with a kind and accepting attitude [1]. The benefits of mindfulness-based interventions for cognitive processing are well documented in both clinical [2] and non-clinical [3] adult populations. These encouraging results have inspired educators, policy makers, and researchers alike to foster mindfulness-based programmes in schools, with developmentally adapted courses. However, the evidence base for school-based programmes is still being established. The initial results in older children and adolescents show reductions in perceived stress, depression, and anxiety, as well as improvements in emotion regulation and executive control [4–7].

Two important factors emphasised in education policy are well-being [8] and metacognition [9]. Well-being in children and adolescents is a growing concern, with one in 10 young people thought to have a diagnosed mental illness, including emotional, attention, and conduct disorders [10]. And beliefs about cognitive ability have been associated with poorer test performance despite an individual's aptitude [11], suggesting an important contribution of metacognition to academic achievement. Initial evidence suggests that school-based mindfulness training may improve well-being [4,5,12]. To our knowledge, no research has investigated links to metacognition, but studies in adults with depression have reported that Mindfulness-Based Cognitive Therapy (MBCT) can increase metacognitive awareness, and such enhancements have been linked to decreased rates of relapse [13]. Metacognition is also related to mind wandering, referring to an individual's attention shifts away from goal-orientated focus, often without awareness [14]. Mind wandering has been shown to reduce after mindfulness practice in adults [15] and a negative relationship was found between mind wandering and well-being in young people [16].

Mindfulness training is often promoted as a well-being enhancing strategy, though a recent systematic review concluded that the strongest effects of school-based mindfulness programmes are on cognitive performance, with emotion and resilience improvements showing only moderate change overall [17]. This might result from the nature of introductory mindfulness programmes in schools, where the overt emphasis is on attention and awareness training through focussed meditation, and there is, understandably, less emotional and experiential group reflection

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(enquiry) than in adult courses. However, recent considerations surrounding the mechanisms of mindfulness-based changes suggest that improvements in emotion processing are the result of enhanced attention processing [18]. This has also been demonstrated experimentally, where mindful attention moderated the relationship between depressive affect and negative cognitions [19]. Therefore, it seems important to investigate how mindfulness practice improves attention in young people, given that this mechanism might have primary (attention) and secondary (emotion processing) outcomes. It is possible that the changes in affective processing induced by school-based programmes only become evident after continued mindfulness practice.

Adolescence is a late catchment period for frontal brain development [20], particularly the prefrontal cortex (PFC) and anterior cingulate cortex (ACC) that are centrally involved in error processing, attention monitoring, and control [21]. Young peoples' impulsivity, for example, directly relates to the undeveloped nature of these frontal regions [22]. Inappropriate impulsivity is associated with a lack of inhibition, a central part of executive attention through which we monitor and control attentional processes [23]. Importantly, mindfulness training has been shown to increase markers of response inhibition and improve selective attention in adults [24]. The PFC and ACC have also been modulated by mindfulness practice, with improvements being found in previous adult magnetic resonance imaging (MRI) and ERP research e.g. [25,26]. It is yet to be determined whether similar gains would be observed in adolescents, but despite their reduced inhibition skills, adolescents' still developing prefrontal regions and attention control processes might present a larger potential for neural plasticity, resulting in more impactful and pronounced effects.

Given the links between impulsivity and adolescent risk-taking behaviours [27], and the added scope for executive attention enhancement in the adolescent population, neuro-cognitive investigations of mindfulness training are of particular interest. In this context, electroencephalographic (EEG) methodologies can be particularly useful for school-based programme research, given their relatively low cost, portability, millisecond temporal accuracy, and reliance on well-established ERP components that index attention functioning [28]. Of particular relevance is the N200 (N2) ERP component, which can be elicited in conflict tasks and is a sensitive marker of response inhibition [29,30]. More negative N2 responses post-mindfulness training indicate better target detection and inhibition of automatic responses, as shown in previous adult research [26]. In terms of target-related information processing, the P300 (specifically the P3b) component is typically assessed, showing modulation as the result of cognitive load [31], although whether this results in a decrease or increase in P3b amplitude depends on the exact task parameters e.g. more positive P300 amplitudes have been associated with reduced target categorisation difficulty [32], and less mind wandering [33]. However, Moore et al. [26] reported that more negative N2 was associated with a subsequent drop in P3b positivity on correct task trials, signifying more efficient attention processing after mindfulness training. Similar P3b reductions, indexing improved attention efficiency have also been reported in studies of extensive meditation training [34]. Another sub-component of the P300 is the P3a, thought to index attention capture to unexpected stimuli [35]. Previous research has found that during meditation practice, P3a-indexed reactivity to unexpected and distracting stimulus is reduced, again indicating at least state-based improvements in attention allocation efficiency [36]. No studies to date have examined mindfulness training effects on inhibition and attention efficiency in adolescents.

The current study investigated the impact of mindfulness training, delivered as part of the school curriculum, on N2 and P300 ERP markers of attention in adolescents. To assess whether mindfulness impacts metacognition, we also examined changes in self-reported mental competency beliefs. These evaluations were conducted before and after a mindfulness-based course, running over one school term in the Personal, Social and Health Education (PSHE) classroom slot, for sixth form students (16–18 years). Sixth form (UK year groups 12 and 13) refers to AS and A-Level students; the highest high school qualifications. Specifically, we hypothesised that mindfulness training would benefit attention performance through increased response inhibition to non-targets as indicated by more negative N2 to non-target stimuli (particularly for non-target stimuli perceptually similar to targets-see methods for detailed predictions), and more positive P3b amplitudes throughout, indexing sustained attention during a visual oddball task. We also expected decreases in P3a to the non-target condition included to assess changes in automatic attention capture (shape deviant non-target). Reductions in self-reported mind wandering during the task, and improvements in metacognitive beliefs were also expected.

2. Methods

The study was approved by the Ethics Committee in the School of Psychology at Bangor University, prior to study commencement.

3. Participants

Participants were recruited from four schools across North Wales, two for the training group and two matched wait-list controls. Sixth form students from all four schools were recruited via presentations explaining the study, and sign-up sheets were then displayed in sixth form common rooms. Participants could volunteer solely for questionnaires, or questionnaires plus ERP recordings during an experimental attention task. Another task focussing on emotion regulation was also part of the testing session, but results are reported elsewhere. For those participating in the ERP section of the study, a time-slot was allocated in January–February (pre-training) and in April–June (post-training) during one of their study periods so as not to interrupt subject lessons. Training group participation was open to all those enroled on the mindfulness-based course, and open to the entire sixth form for control school students. This resulted in $N=47$ (training group$=22$) students who completed the computerised odd-ball attention task and questionnaire measures at both time-points, and a subset of 40 participants (training group$=19$) with pre-post-ERPs. Two intervention group students completed the questionnaires and computerised attention tasks, however they were determined ineligible for study analysis inclusion. One student attended only one session of the mindfulness course, and the other performed at 14% target accuracy during the odd-ball task at baseline, suggesting a lack of comprehension. From the $N=45$ remaining, two participants withdrew from EEG testing but completed the computerised task and questionnaires, and three were removed from ERP analysis due to low trial sweep count and too many artefacts in the EEG files.

The average age of participants in the training group was 16.6 years (SD$=0.6$) and in the control group 17.1 years (SD$=0.6$). This is a representative average for the sixth form cohort. There were significant group differences in age ($t(43)=-2.742$, $p=.009$), as more A-level (year 13) students volunteered in the control schools, equating to them being 6-months older than training group students on average. However the difference between 16 and 17 year olds in developmental terms is minimal [37,38]. Chi squared analyses were run for gender, as well as previous experience of mindfulness, and whether participants already practiced stress relief or mental skills training techniques at baseline. No group

Table 1
Socio-demographics across participant groups at baseline.

	Age: mean (SD)	Unplanned absences: mean (SD)	GP visits: mean (SD)	Gender ratio (F:M)	% with stress relief training	% with mental skills training	% with mindfulness knowledge
Sociodemographics for all participants ($N=45$)							
Training Group	16.6 (0.6)	4.0 (3.6)	1.1 (2.4)	10:10	55	30	0
Control Group	17.1 (0.6)	4.8 (5.3)	0.5 (1.0)	17:8	64	32	8
Sociodemographics for ERP participants ($N=40$)							
Training Group	16.6 (0.6)	3.9 (3.7)	1.1 (2.4)	9:10	57.9	31.6	0
Control Group	17.0 (0.6)	4.4 (5.2)	0.4 (0.9)	13:8	66.7	38.1	9.5

differences were found on any of these measures (all $ps > .05$). The same was true of participants included in the ERP analysis, where only age showed a significant difference between groups ($t(38) = -2.476$, $p = .018$). A summary of means and standard deviations (SD) can be seen in Table 1.

Students were not paid for their participation, but did gain first-hand experience of neuroscientific testing procedures and benefited from additional volunteer hours for their university applications and curriculum vitas. Neuroscience of mindfulness talks, delivered by the first author (KS) were additionally offered to all schools involved.

4. Measures

4.1. The following self-report measures were included

The Five-Facet Mindfulness Questionnaire (FFMQ) [39] was used to assess changes in mindfulness score pre-post-training, and has been effectively used with adolescents [40]. It has 39-items and contains five subscales; 'Observing, Describing, Acting with Awareness, Non-Judging, and Non-Reacting'. The final score can be calculated as FFMQ-Total for all questions, or separated out into subscales. All subscales and total-FFMQ were used in this study. The internal consistencies (Cronbach α) for these facets have been reported as 0.83 for FFMQ-O, 0.91 for FFMQ-D, 0.87 for FFMQ-AwA, 0.87 for FFMQ-NJ, and 0.75 for FFMQ-NR [39]. A higher score indicates a more mindful disposition.

The Meta-Cognitions Questionnaire – Adolescent Version (MCQ-A) [41] recorded changes in students' perceptions of their mental abilities and behaviours. It consists of 30-items split into five subscales, and uses a 4-point Likert scale similar to the adult version. It can be scored as a sum of all questions or split into its subscales, the total and subscales were used in this study. The reliability of the MCQ-A is fair, with subscales reporting internal consistencies of 0.88 for Positive Beliefs, 0.84 for Uncontrollability and Danger, 0.81 for Cognitive Confidence, 0.66 for Superstition, Punishment, and Responsibility (SPR), and 0.79 for Cognitive Self-Consciousness. The reliability for the measure as a total score was reported as 0.91 [41]. A lower score indicates healthier metacognition, with items for Positive Beliefs and Cognitive Confidence asked negatively e.g. "I need to worry in order to work well" is an item on the Positive Beliefs subscale.

A mind wandering measure was designed for the study to record the amount of state mind wandering participants experienced during the attention task. This included a 6-point Likert scale responding to the question "During *block X* how much did you mind wander?" where a higher score indicated more mind wandering. Participants were asked to rate their mind wandering after each of the three attention task blocks.

An acceptability measure was designed for the study, asking mindfulness trained students to rate their enjoyment of the curriculum, and how frequently they practiced at home. Course enjoyment was measured on a 7-point Likert scale (1 = Not at all to 7 = Very much) and home practice was measured on a 4-point Likert scale (1 = Never to 4 = Every day). Mindfulness course attendance was also measured.

5. Computerised task

The attention task followed an oddball design with four simple shapes – three diamonds and one shape deviant non-target star. The standard frequent non-target stimulus (70% of trials) was a dark blue diamond, 15% larger than all other shapes seen during the task. The target stimulus was also a dark blue diamond (10% of trials), but smaller than the standard stimulus. There was a colour deviant non-target oddball (10% of trials), which was the same size and shape as the target, but pale blue in colour. The shape deviant non-target oddball (10% of trials) was a star shaded the same dark blue as target and standard stimuli, and was of equal size to the other task oddballs. Participants were instructed to respond only when they saw the target stimulus appear, pressing the space bar of a keyboard. No response was required to any other stimuli. Fig. 1 shows examples of the stimuli within the task, which was split into three blocks, each with 130 trials displayed randomly within that block (131 in the last block). Each block contained the same proportion of stimuli – 70% for the frequent non-target, 10% for the target, 10% for the colour deviant non-target and 10% shape deviant non-target. All stimuli appeared one at a time in the centre of the computer screen, and presentation order was random within each of the three blocks. Participants were informed beforehand of what to expect during the task, but they did not know that a shape deviant non-target would infrequently appear. The shape-deviant non-target, and colour deviant non-target oddballs were included to separate the effects of inhibition (N2) and automatic attention orienting (P3a). Specifically, we expected that the standard stimulus, and oddball most perceptually similar to the target (colour deviant non-target) would produce a more negative N2 than the perceptually more distinctive non-target oddball (shape deviant). With regards to the P3a, we predicted more positive P3a amplitudes in response to the shape deviant non-target, which participants did not anticipate appearing in the task.

Overall, participants saw 40 trials of each oddball and 271 standard stimuli. Stimuli were displayed for 900 ms, with an inter-stimulus interval of 700 ms. It took 10.5 min to complete the task, with breaks between each block where students were asked to rate their levels of mind wandering.

6. Mindfulness-based school training programme

An age appropriate mindfulness-based school curriculum (.b Foundations), designed for adults and educators was delivered. This course was chosen instead of the standard '.b' curriculum intended for secondary school pupils to reflect the maturity of the

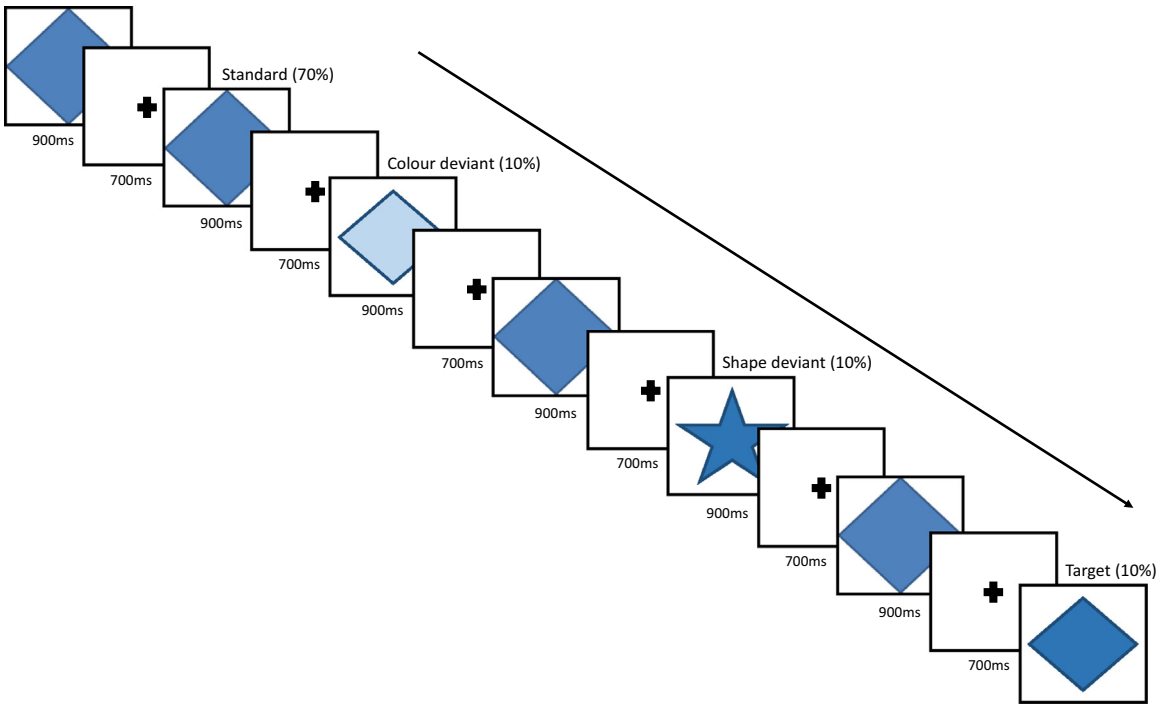

Fig. 1. Oddball task design.

age group targeted for this intervention. The .b Foundations programme was created by the Mindfulness in Schools Project (MiSP; http://mindfulnessinschools.org/) team and draws strongly from Mark Williams and Daniel Penman's 'Mindfulness: Finding Peace in a Frantic World' [42]. The course was delivered over eight 50-min. weekly sessions plus an initial orientation session, taught by students' regular teachers within the PSHE curriculum slot. This is a relatively new model of delivering mindfulness-based courses in schools, which have typically been taught by external mindfulness trainers. The implementation model involved a long-term commitment from teachers, who first completed a prolonged period of mindfulness instruction themselves. This consisted of the .b Foundations course taught over six weeks, three months of individual practice to establish comprehension, and then 14-h training in how to deliver the .b Foundations course to sixth form students. Teachers only proceeded to this last training phase if they wished to continue, and showed a sufficient personal mindfulness practice as assessed by an experienced mindfulness trainer. Supervision from the trainer was also given during the student course period. Control schools were offered the same training after data collection was completed.

7. Procedures

This experiment used a non-randomised pre-post-intervention study design, with wait-list control group, assessing training feasibility as well as underlying neurocognitive mechanisms. Participants were tested individually during school hours, scheduled within personal study periods, using a portable EEG system consisting of acquisition and stimulus presentation laptops, Neuroscan NuAmp amplifier, and EEG cap. Quiet testing spaces were provided on school premises. At baseline all procedures were explained to participants, and informed consent was obtained before the start of testing. EEG volunteers were asked to come to their appointments with clean, dry hair and not to apply hair products or conditioner. During the set-up period, students could complete the FFMQ and MCQ-A as part of a battery of questionnaires. If these were not completed during the set-up time, students took these measures away in a plain envelop and were asked to return them to the experimenter on the next school day. Students only completing questionnaires were handed sealed envelopes with the battery of assessments. Consent forms were enclosed along with information sheets and contact details of the PI if they had any follow-up questions. Completed forms were requested to be handed back to the PI within one week.

EEG signal was recorded with 36 Ag/AgCl electrodes, with the right mastoid as the reference site and Fpz as the ground. Data was obtained with Neuroscan NuAmp amplifiers, utilising a sampling rate of 1 kHz. Two electrodes, situated above and below the right eye, recorded ocular movements. Additionally, two electrodes were placed on either forearm to record heart rate variability, and results of this analysis will be reported elsewhere. The impedance of all electrodes was kept at less than 7 kΩ. Online, the EEG signal was filtered with a bandpass filter range of 0.01–200 Hz, and an additional filter was applied offline with a zero shift low pass setting of 30 Hz, 48 dB/Oct slope. ERP data was cleaned manually by rejecting motor and irregular ocular artefacts, after which an algorithm in Neuroscan Edit software was employed to regress out eye-blinks, and later to remove residual artefacts. The data was epoched into 1100 ms segments starting at −100 ms, and baseline corrected using the signal 100 ms before stimulus onset. Finally, averages for each condition and participant, as well as grand averages across participants for each condition and group were computed.

The attention task was preceded by a short practice block (seven standard trials and one of each odd-ball). Between each block the experimenter asked participants to rate how much they noticed themselves mind wandering during the preceding block, ranging from "Not at all" to "All the time". Clean towels, sensitive skin wipes, and individually labelled hair brushes were supplied for participants so that they could remove most of the electrolyte gel before returning to class.

8. Data analysis

Pre-post-questionnaire measures were analysed using mixed

factorial ANOVAs with a 2(time: pre, post) × 2(group: training, control) design. Significant effects were followed up with paired sample *t*-tests. Outliers more than 2 standard deviations from the mean for that measure were removed prior to analysis, and any violations of sphericity were corrected for, using the Greenhouse-Geisser correction.

ERP analysis was carried out in the same way, with ANOVAs assessing mean amplitude and latency data for electrodes of interest. Initial ANOVAs were run with factors of 4(condition: target, colour deviant non-target, shape deviant non-target, standard non-target) × 2(time) × 2(group) × *n*(electrode) for the N2, P3a, and P3b components (Figs. 4–6). Where significant main effects of condition and interactions were found, separate ANOVAs with factors of time, group, and electrode were conducted. All analysable trials were included in the ERP analyses, as discarding incorrect trials would also remove any ERP differences resulting from mind-wandering, which was a core interest in this study. Removal of incorrect trials would radically shift the scope and predictions of the study. This is because higher amplitudes in the current task, associated with higher accuracy and sustained attention, were linked to less mind wandering based on previous literature [33]. By contrast, with incorrect trials removed, lower amplitudes would be considered to reflect more efficient attention processing (e.g., 26; 34), and would not measure mind wandering.

Correlation and step-wise multiple regression was used to assess the moderating effects of course engagement, as there have been contrasting findings regarding the impact of practice frequency [43,4]. MCQ-A data was additionally correlated with ERP responses to verify the efficacy of this measure as an index of attention control and mental responsiveness.

The electrode sites of interest were based on previous literature, and visual inspection of peak activity in Neuroscan Edit. Mean amplitudes were used in all ERP analyses. The following clusters of electrodes were selected for analyses for each of the components based on previous literature and maximal signal: N2-AFz, Fz, F3 and F4, in the time window 270–330 ms; P3a-Cz, C4, CPz, CP2, and CP4, in the time window 370–430 ms; P3b-CP1, CP2, Cz, and CPz across the time window 330–490;ms.

9. Results

9.1. Acceptability

One intervention participant did not complete this questionnaire, leaving the training group sample as $n=19$. Students reported to have generally enjoyed the course, giving it an average of 65% (5 out of 7). Furthermore, 58% reported practicing often or every day during the programme and 84% were considering keeping up the practice in future. Class attendance records were also checked, with students on average attending 82% of the 8-week course.

10. Five-Facet Mindfulness Questionnaire

One control participant did not complete this questionnaire, bringing the total sample to $N=44$. The mixed ANOVA for FFMQ-Total reported no significant main effects of time ($F(1,42)=.5$, $p=.47$, $\eta^2=.01$), group ($F(1,42)=.1$, $p=.80$, $\eta^2=.002$) or significant time*group interaction ($F(1,42)=.1$, $p=.83$, $\eta^2=.001$). No subscale main effects or interactions were significant (all $ps>.1$).

11. Mind wandering

The mixed ANOVA for mean self-reported mind wandering over the three attention trial blocks reported no significant main effects of time ($F(1,43)=.4$, $p=.52$, $\eta^2=.01$), group ($F(1,43)=1.3$, $p=.26$, $\eta^2=.03$), or significant interaction effect ($F(1,43)=1.4$, $p=.24$, $\eta^2=.03$). Mind wandering was also assessed for those students included in the ERP analysis. This subset of participants resulted in non-significant main effects of time ($F(1,38)=.8$, $p=.38$, $\eta^2=.02$), and group ($F(1,38)=.9$, $p=.35$, $\eta^2=.02$), but there was a significant time*group interaction ($F(1,38)=5.1$, $p=.03$, $\eta^2=.12$). The follow-up *t*-tests revealed a significant increase in control group mind wandering over time ($t(20)=-2.7$, $p=.014$, $d=.59$).

12. Meta-Cognitions Questionnaire – Adolescent Version

One participant from the intervention group and four from the control group did not complete the MCQ-A, leaving the final sample for this questionnaire as $N=40$. Additionally two outliers from the intervention group with values above 2 SD from the mean were removed, resulting in a sample of $N=38$. The MCQ-A Total ANOVA showed a general reduction in scores over time ($F(1,36)=6.3$, $p=.02$, $\eta^2=.13$), non-significant group main effect ($F(1,36)=.8$, $p=.37$, $\eta^2=.02$), and significant time*group interaction ($F(1,36)=6.1$, $p=.02$, $\eta^2=.13$). Follow-up paired samples *t*-tests reported this to be due to a significant decrease in MCQ-A Total score in the training group ($t(16)=2.7$, $p=.02$, $d=.64$) with the control group not showing a significant change ($p>.1$). On visual inspection it appeared that there was a discrepancy between training and control groups at baseline, as can be seen in Fig. 2. However, independent *t*-test confirmed that after removal of the two outlier participants this group difference was non-significant ($t(36)=1.7$, $p=.09$).

The Positive Beliefs subscale showed an overall increase over time ($F(1,36)=8.0$, $p=.008$, $\eta^2=.17$), non-significant main effect of group ($F(1,36)=.001$, $p=.98$, $\eta^2<.001$) and marginally significant interaction ($F(1,36)=4.0$, $p=.054$, $\eta^2=.08$). Paired *t*-tests showed this to be due to a significant increase on the Positive Beliefs subscale for control group participants pre-post ($t(20)=-3.2$, $p=.004$, $d=.70$), indicating that they increased in their reliance on worry and anxiety in order to motivate action. There was no change on this scale in the training group ($p>.1$). For the Uncontrollability, and Cognitive Confidence subscales, ANOVA results showed no significant main effects or interactions (all $ps>.1$). The Superstition, Punishment, and Responsibility (SPR) subscale reported general decrease in scores over time ($F(1,36)=15.7$, $p<.001$, $\eta^2=.27$), non-significant main effect of group ($F(1,36)=2.0$, $p=.16$, $\eta^2=.05$), and significant time*group interaction ($F(1,36)=6.0$, $p=.02$, $\eta^2=.10$). Follow-up *t*-tests confirmed this to be due to a significant reduction in SPR score for the training group ($t(16)=4.7$, $p<.001$, $d=1.15$) with no change observed in the control group ($p>.1$). Cognitive Self-Consciousness showed an overall reduction in score over time ($F(1,36)=6.3$, $p=.02$, $\eta^2=.14$), but no significant effect of group ($F(1,36)=2.3$, $p=.14$, $\eta^2=.06$) or significant interaction ($F(1,36)=1.4$, $p=.25$, $\eta^2=.03$) was obtained (Table 2).

13. Attention task performance

Table 3 summarises attention task performance; no false alarms to the shape deviant non-target were recorded so this is not included in the table. For target accuracy, there were non-significant main effects of time ($F(1,43)=.2$, $p=.7$, $\eta^2=.01$), group ($F(1,43)=2.4$, $p=.13$, $\eta^2=.05$), and a non-significant time*group interaction ($F(1,43)=1.7$, $p=.20$, $\eta^2=.04$). Regarding false alarms to the colour deviant non-target, the main effect of time was significant ($F(1,40)=25.5$, $p<.001$ $\eta^2=.39$) showing a general reduction in false alarms over time, while the main effect of group

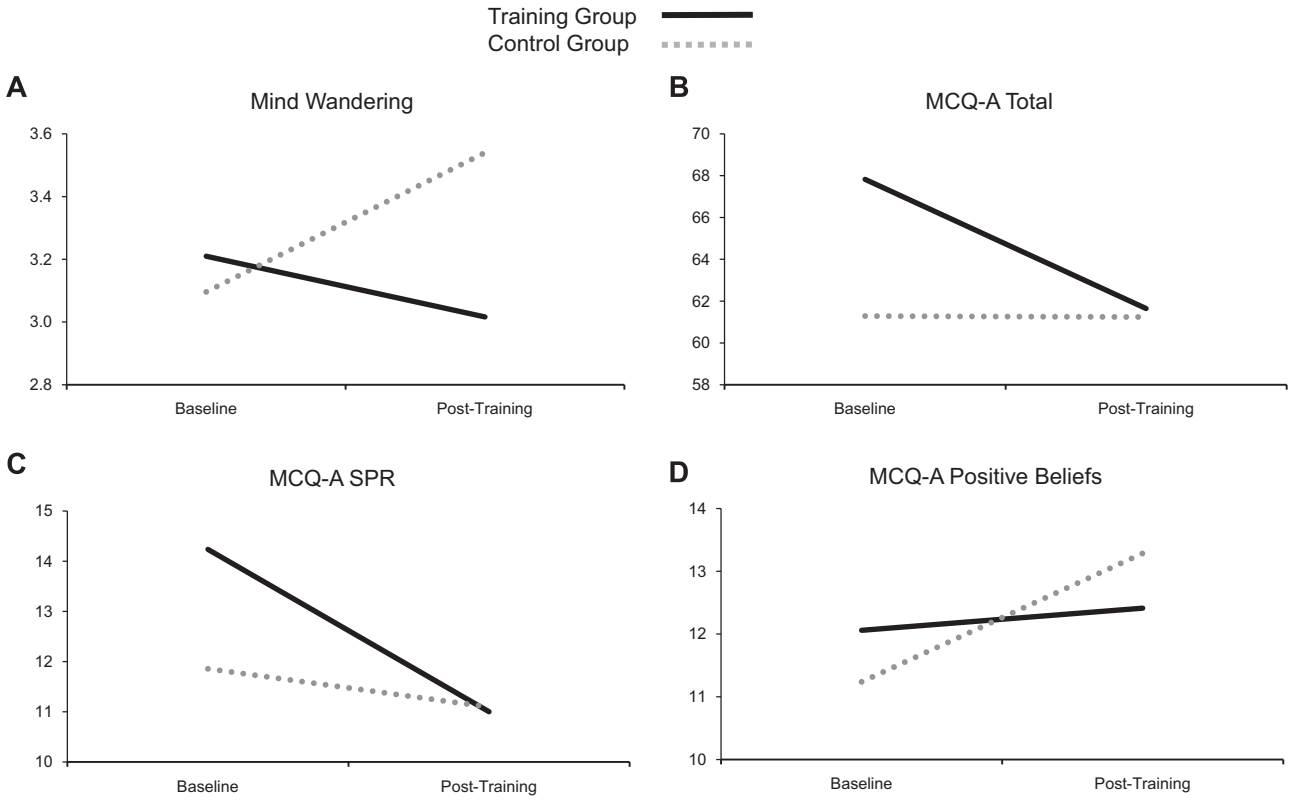

Fig. 2. Mean pre-post-changes in self-report measures between groups: mind wandering (A), MCQ-A Total (B) and MCQ-A SPR (C) significant $p < .05$; MCQ-A Positive Beliefs (D) $p = .054$.

Table 2
Means and standard deviations across participant groups for questionnaire measures. Significant results ($p < .05$) highlighted in bold.

	Questionnaire means (SD)			
	Pre-training group	Post-training group	Pre-control group	Post-control group
FFMQ-Total	118.6 (14.6)	119.3 (13.4)	119.4 (16.1)	120.7 (15.1)
FFMQ-O	24.0 (5.5)	24.1 (4.8)	23.9 (5.2)	23.3 (4.9)
FFMQ-D	25.1 (5.8)	23.8 (4.0)	25.4 (6.6)	25.4 (5.8)
FFMQ-AwA	23.9 (5.5)	23.5 (4.6)	23.8 (6.8)	23.3 (5.8)
FFMQ-NJ	26.1 (6.2)	27.6 (5.9)	26.6 (6.4)	28.1 (5.8)
FFMQ-NR	19.6 (3.3)	20.4 (3.3)	19.8 (4.5)	20.6 (3.5)
MindWandering ($N=45$)	3.2 (0.8)	3.1 (0.9)	3.3 (0.9)	3.5 (0.8)
MindWandering ($N=40$)	3.2 (0.8)	3.0 (0.8)	3.1 (0.8)	3.5 (0.9)
MetaCog-Total	69.5 (11.6)	65.1 (15.4)	61.3 (12.1)	61.2 (13.8)
MetaCog-PosBeliefs	12.3 (4.0)	13.4 (4.2)	11.2 (4.0)	13.3 (4.3)
MetaCog-Uncontrollability	15.2 (3.9)	13.8 (4.8)	12.9 (4.1)	12.4 (4.2)
MetaCog-Cognitive Confidence	12.8 (3.8)	11.7 (4.2)	11.7 (4.1)	12.3 (5.7)
MetaCog-SPR	14.5 (3.0)	11.8 (3.5)	11.9 (3.1)	11.1 (3.0)
MetaCog-SelfConsciousness	14.8 (3.1)	14.4 (4.2)	13.6 (2.9)	12.1 (2.4)
Mindfulness Course Attendance %	NA	81.9 (0.2)	NA	NA
Mindfulness Course Satisfaction %	NA	65.0 (0.3)	NA	NA

and the time*group interaction were non-significant (all $ps > .05$). False alarm data are reported after the removal of three outliers. ANOVA results for all other performance related measures, i.e. reaction time, reaction time variability, and false alarm responses to the standard stimulus were non-significant (all $ps > .05$).

Training group participants' self-reported enjoyment of the course significantly correlated with target accuracy difference, calculated by subtracting baseline accuracy from the post-test accuracy rates ($r = .45$, $p = .05$), *see* Fig. 3. No significant correlations were reported with course attendance ($r = .28$, $p = .23$) or amount of home practice ($r = .22$, $p = .36$). This was supported by step-wise multiple regression, where only course enjoyment explained enough of the variance to be included in the model. The adjusted R^2 reported that student's enjoyment of the mindfulness course accounted for 16% of the variance in training group target accuracy improvement over time.

14. ERP analysis

Table 4 shows the mean number of trials included in the averaged ERP analysis per task condition, with the averages for oddball conditions ranging from 38.3 to 39.5.

15. N200 analysis

To evaluate the predicted differences in response inhibition across the non-target conditions, mean amplitude analysis for the N2 component was conducted at frontal electrodes AFz, Fz, F3 and F4 within the time window 270–330 ms. The EEG signal was maximal at Fz, and this electrode was therefore used to derive peak latencies. An initial ANOVA assessed the independence of task conditions, using a 2(time: pre, post) × 4(condition: standard, colour deviant, shape deviant, target) × 4(electrode: AFz, F3, F4, Fz) × 2 (group: training, control) design. This showed a significant main effect of condition ($F(2.5, 93.3) = 10.4$, $p < .001$, $\eta^2 = .12$), and condition*group interaction ($F(2.5, 93.3) = 4.2$, $p = .013$, $\eta^2 = .05$) suggesting that mean amplitude varied between groups dependent on stimulus type. All other main effects and interactions were non-significant (all $ps > .1$). Since one outlier was identified (with means

Table 3
Mean performance percentages and SDs across participant groups for the oddball task.

	Oddball task performance mean percentages % (SD)									
	Pre-target RT	Post-target RT	Pre-target accuracy	Post-target accuracy	Pre-target omissions	Post-target omissions	Pre-false alarms to colour-deviant	Post-false alarms to colour-deviant	Pre-false alarms to standard	Post-false alarms to standard
Training group	520.2 ms (46.4)	527.6 ms (51.5)	83.5 (11.0)	86.0 (9.1)	16.5 (11.0)	14.0 (9.1)	5.1 (5.4)	1.6 (2.0)	3.2 (6.5)	1.6 (3.2)
Control Group	519.1 ms (47.2)	522.5 ms (49.9)	89.4 (8.8)	88.2 (10.5)	10.6 (8.8)	11.8 (10.5)	4.8 (6.2)	1.4 (4.2)	2.9 (5.9)	1.2 (1.4)

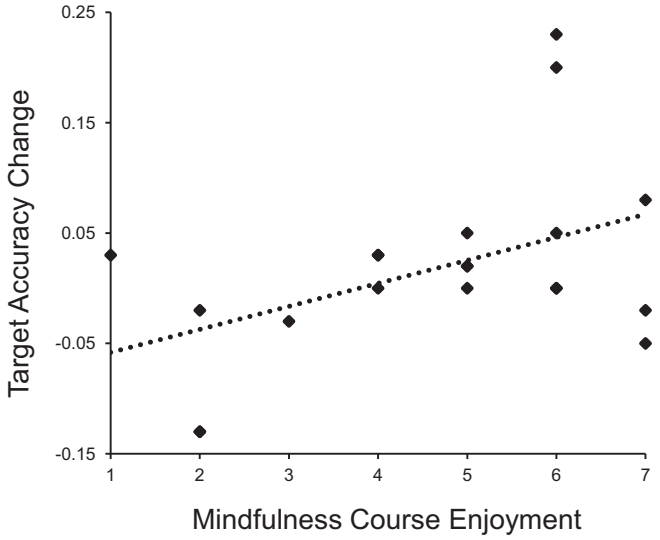

Fig. 3. Significant positive correlation between changes in target accuracy and self-reported mindfulness course enjoyment within the training group ($r=.45$).

2 SD outside of group mean), the ANOVA was re-run using $n=39$ to ensure that the original results were not skewed by this participant's data. This revealed a significant main effect of condition ($F(3, 111)=9.9$, $p<.001$, $\eta^2=.11$), as well as condition*group ($F(2.5, 91.3)=5.6$, $p=.001$, $\eta^2=.06$) and time*condition*electrode*group ($F(6, 221.7)=2.3$, $p=.039$, $\eta^2<.01$) interactions. No other main effects or interactions were significant (all $ps>.1$). The significant main effect of condition and interactions were further investigated in separate ANOVAs for each of the conditions.

Shape deviant non-target: The results of the mixed factorial ANOVA showed a significant main effect of group ($F(1,37)=4.3$, $p=.05$, $\eta^2=.10$), suggesting that the intervention group overall expressed more pronounced N2 negativity to shape-deviant oddballs. All other main effects and interactions were non-significant (all $ps>.05$). There were no significant effects for the ANOVA on latency, and no correlations with MCQ-A (all $ps>.1$).

Colour deviant non-target: The ANOVA showed a marginal Time*Electrode*Group interaction ($F(3, 111)=2.1$, $p=.10$, $\eta^2<.01$) only (no other significant main effects or interactions, all $ps>.1$). Reviewing the descriptive statistics for the data identified an outlier (individual mean amplitudes outside of 2 SD for the group), so the analysis was re-ran with $n=38$, revealing a marginally stronger Time*Electrode*Group interaction ($F(3, 108)=2.2$, $p=.09$, $\eta^2<.01$). No other main effects or interactions were significant (all $ps>.1$). As previous adult mindfulness-training studies have found N2 modulations during attention tasks [26], this marginal effect was followed-up for each electrode. More N2 negativity was found post-test in the training group at electrode F4 ($t(18)=2.0$, $p=.06$, $d=.46$) only, while no modulation was seen in controls at any electrode ($p>.1$). There were no significant main effects or interactions for N2 latency (all $ps>.1$). Correlation analysis was used to assess any converging evidence from MCQ-A change alongside N2 modulation. Pre-post-difference scores on the Uncontrollability and Danger ($r=.35$, $p=.04$) and marginally Cognitive Confidence ($r=.32$, $p=.06$) subscales of the MCQ-A were found to positively correlate with N2 mean amplitude change, indicating that more negative N2 post-training was also associated with an obtained drop in perceived uncontrollability and improved cognitive confidence. Within the training group specifically, correlation analysis also investigated potential contributions to N2 modulation by self-reported course enjoyment, attendance, and home practice, but no significant effects were found.

Standard non-target: Analysis for this condition was of interest since N2-marked inhibition to the standard stimulus would be expected after mindfulness training, and improvement over time would indicate more efficient attention processing. There was a significant time*group ($F(1,37)=6.9$, $p=.01$, $\eta^2=.1$) interaction effect. No other significant main effects or interactions were found (all $ps>.1$). Therefore a follow-up paired sample t-test was performed on averaged electrode mean amplitudes pre-post, revealing the ANOVA effect to be due to significantly more negative N2 amplitudes over time in the training group ($t(18)=3.3$, $p=.004$, $d=.76$). There were no significant changes in the control group ($p>.1$). Additionally, there were no significant main effects or interactions for latency or correlations with MCQ-A change scores (all $ps>.1$).

Target: As expected the ANOVA for target stimulus revealed a main effect of electrode only ($F(3, 111)=2.9$, $p=.04$, $\eta^2=.01$). No main effects or interactions were revealed for latency, or correlations with MCQ-A (all $ps>.1$).

16. P3a analysis

The EEG signal for the P3a was maximal at CP4 (where latency was derived). Mean amplitudes across a right-sided central parietal cluster Cz, C4, CPz, CP2, and CP4 were examined between 370–430 ms. A 2(time: pre, post) × 4(condition: standard, colour deviant, shape deviant, target) × 5(electrode: Cz, C4, CPz, CP2, CP4) × 2(group: training, control) ANOVA was run. We found a significant main effect of time indicating significant decrease in amplitudes by post-test ($F(1,38)=5.3$, $p=.03$, $\eta^2=.01$), and significant difference in mean amplitudes between conditions ($F(3114)=15.8$, $p<.001$, $\eta^2=.16$). There was also a significant time*condition interaction ($F(1,93.5)=2.9$, $p=.04$, $\eta^2=.01$). Follow up analyses showed that, as expected, the mean amplitudes were maximal for the shape deviant non-target oddball, and similarly, most of the variation over time was in response to the shape deviant stimulus. However, there were no interactions with time or group (all $ps>.1$) so no further analysis was undertaken. The ANOVA for latency showed no significant main effects or interactions (all $ps>.1$).

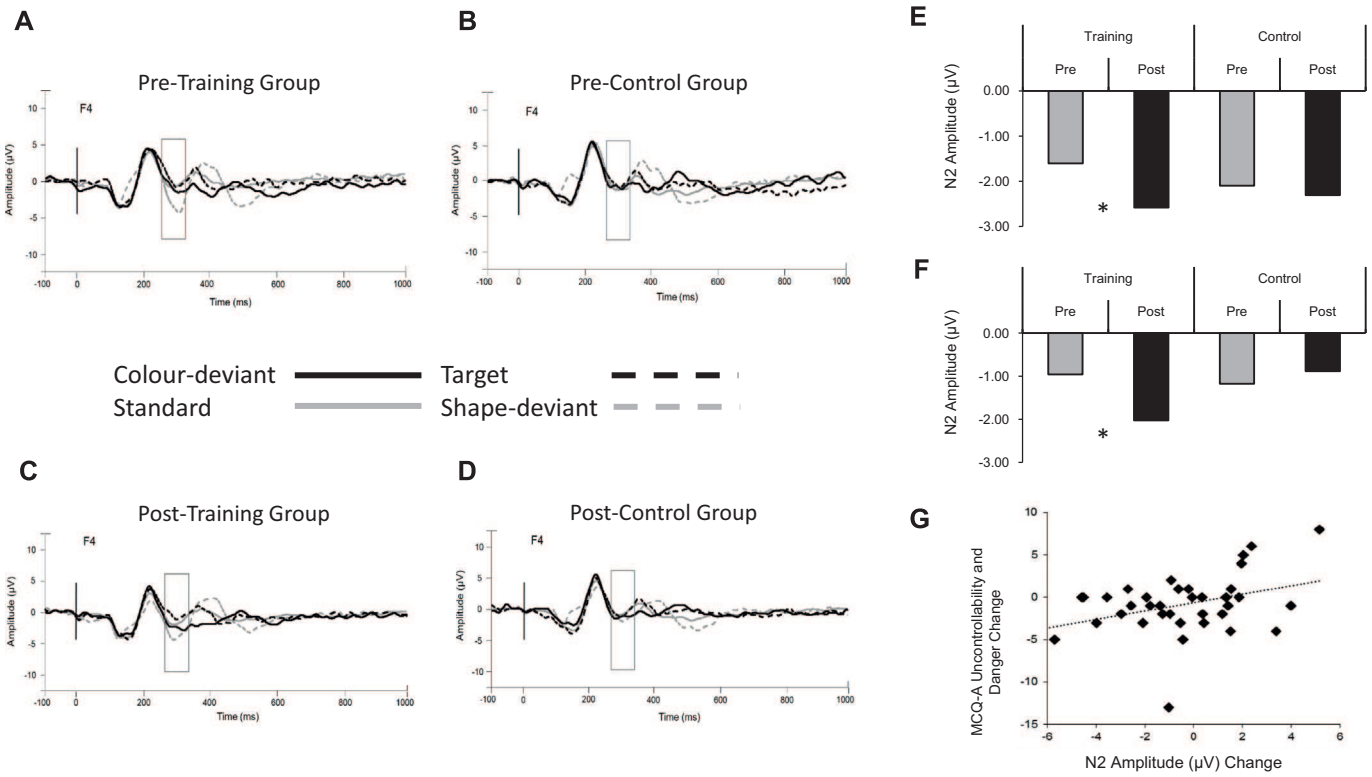

Fig. 4. Graphs A–D show general average waveforms highlighting the N2 time window. Graph E represents the N2 mean amplitude change for the distractor condition with marginal modulation in the training group ($p = .09$), and graph F shows N2 mean amplitude change for the frequent stimulus condition showing significant change in the training group ($p = .01$). The correlation plot (G) shows the significant positive correlation ($p < .05$) between N2 mean amplitude change to distractor stimuli and improved score on the MCQ-A Uncontrollability and Danger subscale.

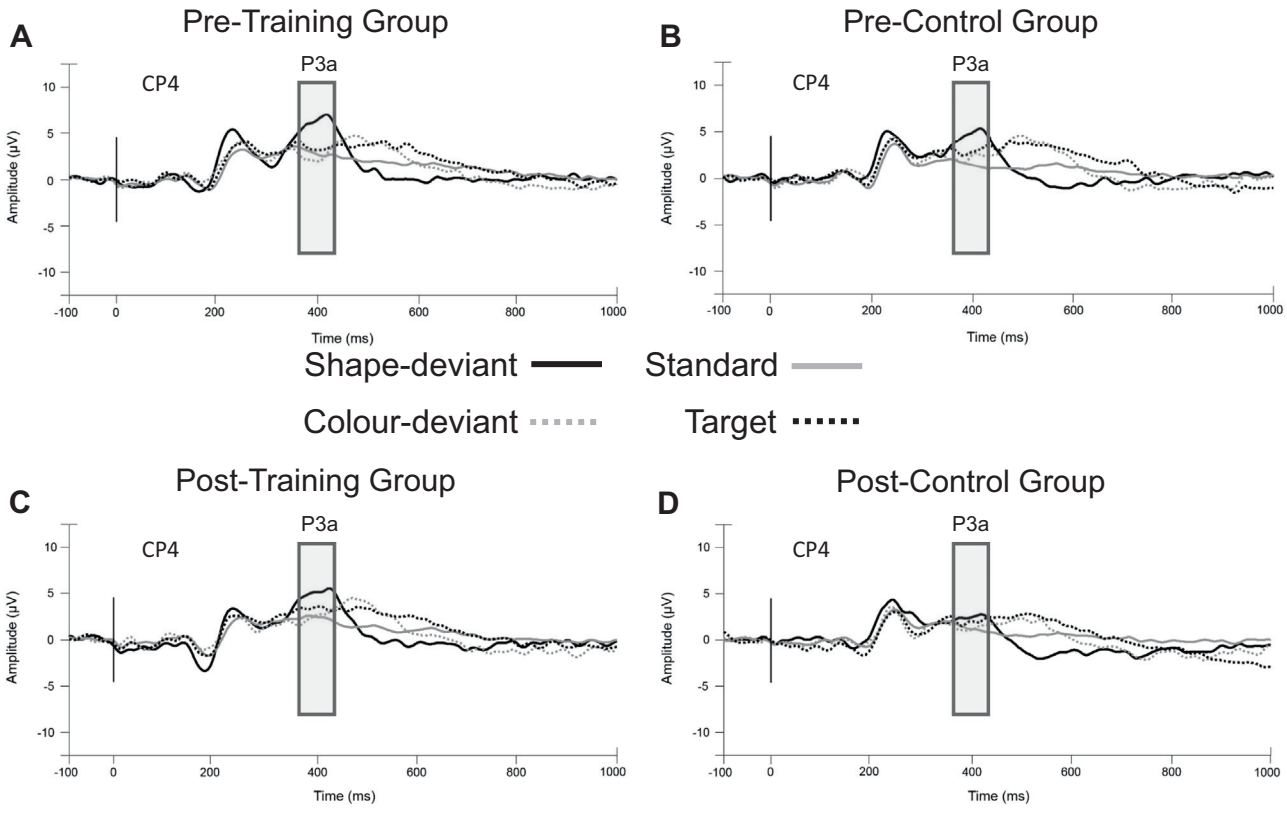

Fig. 5. Graphs A–D show general average waveforms highlighting the P3a time-window.

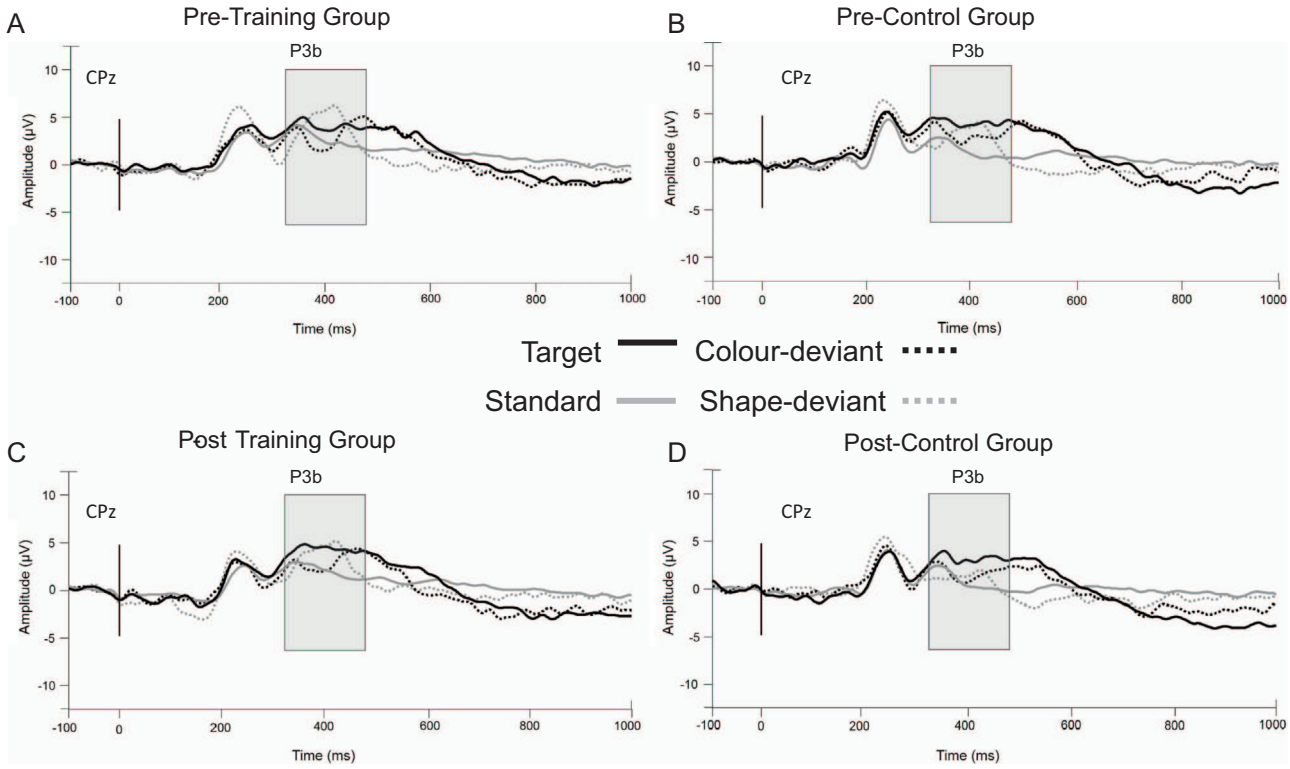

Fig. 6. Graphs A–D show general average waveforms highlighting the P3b time-window.

17. P3b analysis

Mean amplitude analysis focused on a right-sided central, parietal cluster of electrodes – CP1, CP2, Cz, and CPz between 330–490 ms. The signal was maximal at CPz, which was used to derive peak latencies. The 2(time: pre, post) × 4(condition: standard, colour deviant, shape deviant, target) × 4(electrode: CP1, CP2, Cz, CPz) × 2(group: training, control) ANOVA showed a significant main effect of time, indicating a decrease in mean amplitude over time ($F(1,38)=6.2$, $p=.02$, $\eta^2=.02$), and significant main effect of condition pointing to neural response differences between conditions ($F(3,77.5)=7.4$, $p=.001$, $\eta^2=.09$). There was also a significant condition*electrode ($F(\ 6227.5)=4.9$, $p<.001$, $\eta^2<.01$) interaction. No other effects were significant (all $ps>.01$). As no significant interactions included time or group there was no suggestion of training impacting P3b modulation, and follow-up analysis was not conducted. The ANOVA for latency showed no significant main effects or interactions (all $ps>.1$).

18. Discussion

To our knowledge, this was the first investigation of the impacts of mindfulness-based training for adolescents in school using neuroscientific methodology. The results showed that a mindfulness-based programme delivered as part of the standard curriculum was acceptable for 16–18 year old students. Importantly, we found that mindfulness training was associated with significantly more pronounced N2 negativity in response to colour deviant and standard non-target stimuli, in a visual oddball paradigm. Moreover, N2 modulation was associated with changes in mental uncontrollability and cognitive confidence as measured by the MCQ-A metacognition questionnaire, showing converging evidence that N2 modulation can index cognitive control processes. Training-based improvements were also noted in self-reported mind wandering and metacognitive beliefs. We found that ERP participants in the control group had more concentration lapses at post-test, and relied more on worry-based motivations to work. By contrast, mindfulness training was associated with reductions in superstitious and self-punishing beliefs about thought content, indicated by a lower score on the SPR subscale of the MCQ-A.

Overall, our findings suggest that mindfulness training for adolescents, delivered by schoolteachers, can have a positive impact on attention processing. Indeed, the pattern of non-significant change in response time and accuracy, coupled with a significant increase in N2 negativity to non-target standard and colour deviant stimuli, is similar to the findings of Moore et al. [26] in adults

Table 4
Mean number of trials per condition included in averaged ERP analysis across participant groups.

	Mean (SD) trials per condition for ERP analysis							
	Pre-target	Pre-colour deviant	Pre-shape deviant	Pre-standard	Post-target	Post-colour deviant	Post-shape deviant	Post-standard
Training group	38.4 (3.0)	38.3 (3.0)	38.3 (2.8)	259.4 (18.6)	39.4 (0.7)	39.3 (1.1)	39.5 (0.8)	267.6 (6.0)
Control group	39.5 (0.7)	38.8 (1.4)	39.2 (1.3)	265.9 (5.0)	39.0 (2.2)	38.8 (1.9)	38.5 (2.5)	260.3 (13.7)

undergoing 16-weeks of brief mindfulness training. Interestingly, the current study found the N2 change to be specific to colour deviant and standard non-target conditions. This would be expected, since these conditions require response inhibition from the participant. This pattern of N2 modulation suggests that adolescents trained in mindfulness-based practices were able to discriminately inhibit responses to task-irrelevant oddball stimuli. No change over time was identified to the shape deviant non-target, which was likely due to the distinctive perceptual difference of the stimulus, resulting in less demanding inhibition of a response. Older adolescence is considered the peak age for orienting attention skill [44], which encapsulates our ability to shift attention between stimuli. This could account for the training group's learning to selectively inhibit responses to irrelevant stimuli after mindfulness practice, instead of increasing N2-marked response inhibition to all stimuli as was reported in an adult study of conflict monitoring after mindfulness training [26].

The selective disengagement from task-irrelevant stimuli noted in mindfulness-trained students could be pertinent to emotion regulation skills in adolescents, though we have not directly assessed this in the current study. Risk-taking behaviours are most prolific in adolescents, and while this can be advantageous for personal development, young people can make hasty decisions when emotionally influenced by peer pressure, known as 'hot cognitions' [20]. The noted improvements in the training group's inhibitory responses, indicated by more N2 negativity, may extend to more emotion-based interference like peer pressure or engagement with negative, ruminative thoughts, as N2 modulation has previously been associated with emotion and attention regulation [45–49]. Indeed, we found an association between the increases in N2 negativity and the uncontrollability subscale of the MCQ-A, which measures an individual's concern about rumination on worry. Therefore, more prolonged mindfulness training may enable adolescents to filter out unhelpful influences and support them to re-allocate their attention resources, thus enabling more balanced decision-making, as suggested in adults [18].

In addition to N2 marked changes in attention, this study found that mindfulness training may positively impact on students' metacognitive beliefs. The mindfulness group reported a significant reduction in metacognitive concerns, with the Superstition, Punishment, and Responsibility subscale in particular showing this decrease. Together with the significant increase in control students' reported reliance on worry, i.e. higher scores on the Positive Beliefs subscale post-test, this suggests that mindfulness may have a 'befriending' effect on how students' relate to their own mind. The training group reported becoming kinder and more accepting of their thoughts, and unlike controls they did not increase in their belief that worry motivates action. This is particularly relevant in the context of the post-test timing of the study, since data collection occurred during the run-up to summer exams, and academic pressures would have been high. This could explain the reliability on worry that control participants expressed, and mindfulness practice may have buffered the training group against this effect. A similar pattern emerged in the mind wandering data, where control students reported increases in their lapses of concentration. This increase was not found in mindfulness-trained students, who maintained their ability to stay present.

Finally, our results indicated that although attention task performance did not change between groups, a significant correlation was found in the training group between self-reported enjoyment of the programme and changes in target response accuracy. No such correlations were found with home practice or class attendance, which have previously been associated with benefits to student well-being [4]. This new link suggests that it might not necessarily be the frequency of mindfulness practice that brings about attention change in adolescents, but the quality of the engagement with practice. This finding could have strong implications for the design of developmentally adapted courses, highlighting the need to ensure that programme delivery is relevant and engaging for students, not merely longer or more frequently administered. More qualitative research to investigate this would be insightful, to gain recommendations on how programme enjoyment can be maximised in schools.

19. Limitations and future directions

The study also had some limitations. The correlation between target accuracy and mindfulness course enjoyment may have been confounded by motivation. It is possible that those students who most enjoyed the mindfulness-based programme were also more motivated to perform well on the computerised task. A similar effect could have contributed to the observed effect on mind wandering. However, the lack of between group improvements in overall target accuracy and response time suggest that this was not the case. Nevertheless, future studies controlling for participant motivation need to be conducted. The changes in metacognition should also be interpreted with caution, as while the groups were not statistically different at baseline ($p = .09$), there was a marginal variance, and therefore inadvertent selection bias may have impacted the results.

The current study, similar to the majority of neuroscience studies on mindfulness, did not include follow-up measurements due to the complexity of EEG data acquisition. However, future research on school-based mindfulness programmes would benefit from including follow-up measurements to assess the possibility of emotion regulation effects being subsequent to improvements in attention processing, as others and we have hypothesised. It is also an open question whether the observed effects are sustained after programme completion.

We did not find the predicted changes in P300 (P3a or P3b) mean amplitude post-training, however the strongest N2 effects were found in response to standard non-targets. Considering that this increased N2 response was sustained over 271 trials, it may be that initial mindfulness training effects impact sustained automatic attention, rather than later information processing that would be indicated by P3b modulations. A lack of P3a effect may have been due to the strong perceptual contrast between the shape deviant stimulus and other task conditions. Future studies could experiment with different ways to study the 'startle' effect after mindfulness training, perhaps using different sensual modalities like sound. Finally, the current study did not investigate links between modulations in N2 and impulsivity, which would be of direct relevance to adolescent risk-taking behaviour.

20. Conclusions

This was the first study in adolescents to document benefits to attention processing and metacognition resulting from mindfulness-based training in school, using event-related potentials. This initial evidence of mindfulness practice encouraging adolescents to more efficiently inhibit irrelevant stimuli, together with enabling them to reduce critical self-judgment, may have implications for academic performance and learning; which would also be relevant to education policy. Indeed, our findings provide further support to the hypothesis that mindfulness practice can contribute to the development of metacognitive awareness and well-being in young adults, potentially supporting their self-efficacy and academic success. As demonstrated in this study, neuroscience research has a strong role to play in helping us further understand the potential and limitations of mindfulness in an educational context.

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