

Abstract

Changes in EEG when moving from an eyes-closed to an eyes-open resting condition result from bottom-up sensory processing and have been referred to as activation. In children, activation is characterised by a global reduction in alpha, frontally-present reductions for delta and theta, and a frontal increase for beta. The present study aimed firstly to replicate frontal EEG activation effects using single-channel, dry-sensor EEG, and secondly to extend current understanding by examining developmental change in children. Frontal EEG was recorded using a single-channel, dry-sensor EEG device while 182 children aged 7-12 years completed eyes-closed resting (EC), eyes-open resting (EO), and focus (FO) EEG tasks. Results indicated that frontal delta, theta, and alpha power were reduced, and frontal beta power was increased, in the EO compared to the EC condition. Exploratory analysis of a form of top-down activation showed that frontal beta power was increased in FO compared to EO, with no differences for other bands. These activation effects were robust at the individual level. The bottom-up activation effects reduced with age for frontal delta and theta, increased for frontal alpha, with no developmental change for top-down or bottom-up frontal beta activation. These findings contribute further to validation of the single-channel, dry-sensor, frontal EEG and provide support for use in a range of medical, therapeutic, and clinical domains.

Keywords

EEG, Frontal, Development, Children, Activation, Arousal

Introduction

The Cognitive Energetic Model (CEM) highlights the role of effort as well as tonic and phasic physiological activity in the efficient engagement of computational/cognitive processes and executive functions, with these factors determining the overall efficiency of information processing¹. The tonic physiological aspect has been referred to as arousal^a, defined as the current energetic level of the organism, and can be measured via skin conductance level (SCL) or brain electrical activity using electroencephalography (EEG). Increases in SCL, indicative of increased arousal, are associated with reductions in EEG power in the alpha frequency band across the scalp². Alpha power has been shown to be an inverse measure of arousal in children³ and adults⁴. The phasic physiological aspect of CEM has been referred to as activation^b, defined as a separable state measure reflecting the task-related mobilisation of energy (relative to a baseline level of arousal) needed for task performance². Activation can be measured by examining the arousal difference between eyes-open resting and eyes-closed resting conditions, with the change in arousal level due to the increased sensory input in the eyes-open condition indicative of activation⁵. As would be predicted by the CEM theoretical framework, activation has been shown to contribute to task performance in adults^{2,6-8} and executive functions (EFs) in children⁹. In children, the most prominent EEG indicator of activation is a global reduction in alpha power in the eyes-open condition, along with more regionally specific reductions in delta (focal frontal reduction, larger in the right hemisphere) and theta (larger reductions in frontal and posterior hemispheric regions) power, and a reduction in beta power in the posterior brain region and an increase in beta power in the frontal region¹⁰.

While EEG activation effects are similar in children¹⁰, young adults⁴, and older adults⁵, it is not known if there is developmental change in arousal or activation during childhood. One aim of the current study was to examine developmental change in the 7-12 year age-range. Changes in arousal and activation are expected, given literature indicating a decline in the absolute power of all bands, especially the slow waves¹¹⁻¹³, along with evidence showing that functional information processing networks become more organized; both linked to structural changes in the brain such as synaptic pruning¹⁴.

EEG activation related to the opening of the eyes primarily results from increased visual system activity¹⁵⁻¹⁷. This type of activation is derived under resting (i.e. no task) conditions is a “bottom-up” process as it results from a simple passive change in sensory input. Another type of activation has also been considered by examining EEG changes from an eyes-open resting baseline to a cognitive task; termed task-related activation¹⁸. The current study sought to explore an extension of the activation concept to consider “top-down” activation resulting from instructed modulation of a psychological state; in this case, attention, in accord with previous work¹⁹. This type of top-down activation, termed “attentional activation” here, aims to provide an index of EEG changes between an eyes-open resting state and an elevated attentional state that is

^a Originally termed *activation* in CEM, but referred to as arousal here in line with an empirically validated definition² widely accepted in the literature.

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less confounded by ongoing task-related cognitive processing, and thus could be considered a relatively pure EEG index of a top-down modulation of attention.

As outlined earlier, previous investigations in this area have considered the topographic nature of EEG in eyes-open and eyes-closed resting conditions. In the current study, we aimed to determine if the established activation effects, all of which were either global or present in the frontal region, could be replicated in a single frontal EEG recording location using a dry-sensor, portable, recording device. Further, we aimed to explore how attentional activation was represented frontally. The single-channel, dry-sensor EEG has established concurrent validity via comparisons to a research system, and comparative validity via sensitivity to variations in psychological state^{20,21}. The EEG is stable within recording sessions²¹ and reliable over short (one-day) and longer (one-week and one-month) retest-intervals²², in accord with lab-based EEG recording systems^{23,24} and fMRI²⁵. In addition to obvious limitation of only having one recording location²⁰, other noted limitations relate to blink detection accuracy²⁶, susceptibility to eye and muscle artifacts²⁷, and estimation of spectral power at frequencies less than 4 Hz^{21,20}. In terms of applications, frontal EEG from a single-channel portable device has been found to identify distinct electrophysiological profiles for stroke patients²⁸, have prognostic value for post-stroke cognitive performance²⁹, and reveal brain activity differences in children with foetal alcohol syndrome³⁰. Further, this frontal EEG has been used in interventions for children with AD/HD³¹⁻³⁴ and anxiety^{35,36}, and found suitable for use in generation of auditory event-related potentials for brain-computer interface (BCI) applications³⁷. Indeed, mobile EEG approaches are thought to have the potential to open unprecedented possibilities in the investigation of psychopathological mechanisms of neurodevelopmental disorders and the identification of EEG biomarkers³⁸.

In summary, the present study aimed to replicate previously reported EEG activation effects in children using frontal, single-channel, dry-sensor EEG, extend current understanding of frontal arousal and activation by considering age effects in a large sample of children, and explore how top-down attentional activation is reflected in the frontal EEG of children. Specifically, it was predicted that the activation effects reported previously in children aged 8-12 years that were either global (e.g. reduction in alpha power) or present in the frontal region despite showing topographic variation (e.g. reductions in delta and theta power, and increase in beta power) would be replicated in the single-channel frontal EEG. Further, it was predicted that frontal EEG indices of arousal and activation would show developmental change in children. A reduction in frontal alpha power in the eyes-closed resting condition, not verified by SCL and thus considered a proxy measure, was used to index increased arousal. No specific predictions were made for attentional activation, rather frontal EEG in each band was examined by comparing an eyes-open resting condition and an instructed attention load condition, with age effects examined.

Materials and Methods

Participants

One hundred and eighty two children aged between 7 and 12 years participated in this study, recruited from three primary schools in the Hangzhou region of China. Three age groups were formed with 70 children in the 7-8 year group (32 female, mean age 7.60 years), 70 children in the 9-10 year group (35 female, mean age 9.51 years), and 42 children in the 11-12 year group (21 female, mean age 11.74 years). Children were excluded from participation if they had a current or previous diagnosis of a psychological or psychiatric disorder, or had an average rating-per-item (ARI) score of 1 or more in DSM-V Inattention or Hyperactivity/Impulsivity symptom categories. Twenty two children from the original sample of 204 were excluded based on the ARI criteria, resulting in the sample described above. Zhejiang Normal University and the University of Wollongong and Illawarra Shoalhaven Local Health District Health and Medical Human Research Ethics Committee approved the research protocol prior to the commencement of data collection. The research was conducted in accordance with the approved guidelines, and each participant's parent(s) gave informed consent.

Materials

The Chinese version of the 40-item SNAP-IV rating scale was completed by each participant's parent³⁹, examining participant's behaviour in terms of DSM-V items for AD/HD and ODD, items from the Conners Index Questionnaire⁴⁰, and items from the IOWA Conners Rating Scale⁴¹, deriving six subscales. The parent form of the Chinese version of the SNAP-IV is both reliable and valid⁴², while the IOWA Conners Rating Scale has good internal consistency and test-retest reliability⁴³. The items are rated on a 4-point scale from (0) 'not at all' to (3) 'very much'. ARI was calculated by averaging ratings for items in the DSM-V Inattention and DSM-V Hyperactivity/Impulsivity symptom categories separately, deriving scores that range from 0 to 3.

Procedure

Each participant's parent(s) completed a demographic and screening questionnaire, and the SNAP-IV questionnaire. Separately, children were seated at a desk in front of a laptop computer, fitted with the EEG recording device, and then completed three EEG tasks with task order counterbalanced between participants. The eyes-open (EO) task required the child to look at a small image (simple smiling face) in the centre of the laptop screen for 2 minutes. The eyes-closed (EC) task required the child to sit with their eyes closed for 2 minutes. In the focus (FO) task children were instructed to "focus hard on the screen for 30 seconds" while viewing a simple coloured shape stimulus which slowly morphed in colour and shape over a 10 s period (e.g. red square morphing into yellow triangle, then morphing into blue square, etc.); there were two 30 s blocks. Participants were instructed to try to remain still during the EEG tasks and to direct their gaze to the stimuli on-screen to minimise muscle and eye movement artifacts. Each participant also completed three executive function tasks and several questionnaires that are not reported here.

EEG acquisition and quantification

Continuous EEG was recorded from a portable EEG device (Mindwave Mobile, Neurosky, San Jose, California) from scalp location FP1 referenced to the left ear at 512 Hz. The device consists of microchips and embedded firmware (ThinkGear, Neurosky, San Jose, California) and a 10 x 15 mm active electrode and ear-clip reference ground electrode contained within a light-weight comfortable headset. Raw EEG data was transmitted wirelessly by Bluetooth to the laptop computer for recording and subsequent off-line quantitative analysis.

EEG from each task was analysed separately using Matlab functions from the ‘Signal Processing’ and ‘Statistics and Machine Learning’ toolboxes. The two 30 s blocks of the FO task were appended for analysis. Firstly, EEG from the 120 s EC task and the 120 s EO task were analysed, to allow comparison. Then, EEG from the 120 s EO task was analysed a second time, with analysis of a randomly chosen 60 s section of the 120 s trace, to allow direct comparison with the 60 s FO task.

Raw EEG data from the Mindwave device was band-pass filtered (4th order Butterworth, 0.5–45 Hz) with traces from the EO and FO tasks subject to an iterative template matching and suppression (IMTS) procedure to detect and suppress blink artifacts⁴⁴. The ITMS approach consists of (1) an iterative process in which blink-artifacts are detected and the blink-artifact waveform is estimated, (2) generation of a signal modelling the blink-artifact, and (3) suppression of the blink-artifact model from the raw EEG. In this paper, the ITMS algorithm was implemented with 10 iterations, and initialized with the original blink-artifact template resampled at the sampling rate of the EEG device (i.e. 512 Hz). The convergence of the algorithm to the blink-artifact morphology of each subject was validated by visual inspection. The EEG traces were then divided into 1 second epochs with a 50% overlap, and windowed with a Hanning window. Epochs containing values exceeding $\pm 150 \mu\text{V}$ were rejected. The remaining epochs were Fourier transformed and magnitude squared to obtain the power spectrum density from which the averaged spectral power (μV^2) was estimated in the four frequency bands: delta (0.5 to 3.5 Hz), theta (3.5 to 7.5 Hz), alpha (7.5 to 12.5 Hz), and beta (12.5 to 25 Hz).

Data analysis

Statistical analysis was carried out using IBM SPSS Statistics version 25, testing a general linear model. Assumptions of normality and sphericity were met for all EEG variables. For EEG epochs, a repeated measures ANOVA was conducted with Condition (EC, 120 s EO) as a within-subjects factor and Age (7-8, 9-10, 11-12 years) as a between-subjects factor, with a similar analysis conducted comparing epochs in the 60 s EO quantification and FO. For arousal, absolute power in the alpha band in the EC condition was subject to a univariate ANOVA with Age (7-8, 9-10, 11-12 years) as a between-subjects factor, with planned contrasts allowing consideration of developmental change by comparing the 7-8 year group to both the 9-10 year and 11-12 year groups. For activation, separate repeated measures ANOVAs were conducted for the absolute power in each frequency band with Condition (EC, EO) as a within-subjects factor and Age (7-8, 9-10, 11-12

years) as a between-subjects factor, with simple effects within each age group separately examined post-hoc. A similar analysis was conducted for attentional activation, with Condition (EO, FO) as the within-subjects factor. Effect sizes for significant Age group comparisons are reported using Cohen's d for groups with equal sample sizes, and Hedges' g for groups with unequal sample sizes. Pearson correlations of arousal and activation were computed for alpha power separately within each age group, to confirm the arousal-activation relationship in frontal EEG.

Results

EEG epochs

There was no significant difference between the number of epochs in the EC ($M = 80.24$, $SD = 27.78$, 95% CI [73.84, 86.63]) and EO ($M = 82.08$, $SD = 28.14$, 95% CI [75.72, 88.43]) conditions, or the 60s EO ($M = 41.47$, $SD = 13.95$, 95% CI [37.89, 45.67]) and FO ($M = 39.79$, $SD = 14.78$, 95% CI [36.41, 43.17]) conditions. In both comparisons, the Condition by Age interaction was not significant.

Frontal EC alpha

Frontal alpha power in the EC condition showed a significant main effect of Age, $F = 4.691$, $p = .010$, $\eta_p^2 = 0.050$, with planned contrasts indicating increased power ($p = .003$, Cohen's $d = 0.51$) in the 9-10 year group ($M = 32.65 \mu V^2$, $SD = 15.33$, 95% CI [29.59, 35.72]) compared to the 7-8 year group ($M = 25.95 \mu V^2$, $SD = 10.53$, 95% CI [22.86, 29.04]) and no significant difference between the 11-12 year group ($M = 30.26 \mu V^2$, $SD = 12.47$, 95% CI [26.30, 34.23]) and the 7-8 year group.

Frontal EC versus EO effects

Frontal delta power showed a near-significant main effect of Age, $F = 2.962$, $p = .054$, $\eta_p^2 = 0.032$, with planned contrasts indicating reduced power ($p = .017$, Hedges' $g = 0.42$) in the 11-12 year group ($M = 51.42 \mu V^2$, $SD = 38.37$, 95% CI [34.89, 67.98]) compared to the 7-8 year group ($M = 76.95 \mu V^2$, $SD = 69.99$, 95% CI [64.03, 89.88]) and no difference between the 9-10 year group ($M = 63.86 \mu V^2$, $SD = 54.36$, 95% CI [51.03, 76.69]) and the 7-8 year group. A main effect of Condition indicated reduced power in the EO ($M = 49.87 \mu V^2$, $SD = 43.66$, 95% CI [43.06, 56.68]) compared to the EC ($M = 78.29 \mu V^2$, $SD = 64.81$, 95% CI [67.57, 89.00]) condition, $F = 59.231$, $p < .001$, $\eta_p^2 = 0.250$. There was a significant interaction between Condition and Age, $F = 4.098$, $p = .018$, $\eta_p^2 = 0.044$, with simple effects revealing the largest reduction in the 7-8 year group ($M_{diff} = 41.69 \mu V^2$, $SD = 39.24$), $F = 29.247$, $p < .001$, $\eta_p^2 = 0.301$, followed by the 9-10 year group ($M_{diff} = 28.67 \mu V^2$, $SD = 19.74$), $F = 46.136$, $p < .001$, $\eta_p^2 = 0.401$, and then the 11-12 year group ($M_{diff} = 14.88 \mu V^2$, $SD = 4.48$), $F = 7.573$, $p = .009$, $\eta_p^2 = 0.156$. See Figure 1.

Frontal theta power showed a main effect of Age, $F = 6.535$, $p = .002$, $\eta_p^2 = 0.067$, with planned contrasts indicating reduced power ($p < .000$, Hedges' $g = 0.62$) in the 11-12 year group ($M = 32.76 \mu V^2$, $SD = 16.83$, 95% CI [25.55, 39.97]) compared to the 7-8 year group ($M = 49.39 \mu V^2$, $SD = 31.43$, 95% CI [43.76,

55.02]) and no difference between the 9-10 year group ($M = 43.11 \mu V^2$, $SD = 25.75$, 95% CI [37.53, 48.70]) and the 7-8 year group. A main effect of Condition indicated reduced power in the EO ($M = 35.44 \mu V^2$, $SD = 21.73$, 95% CI [31.96, 38.95]) compared to the EC ($M = 48.07 \mu V^2$, $SD = 27.42$, 95% CI [43.63, 52.51]) condition, $F = 47.768$, $p < .001$, $\eta_p^2 = 0.212$. A significant interaction between Condition and Age, $F = 3.236$, $p = .042$, $\eta_p^2 = 0.035$, and follow-up simple effects indicated that the largest reduction was in the 7-8 year group ($M_{diff} = 18.40 \mu V^2$, $SD = 8.05$), $F = 23.772$, $p < .001$, $\eta_p^2 = 0.259$, followed by the 9-10 year group ($M_{diff} = 12.83 \mu V^2$, $SD = 5.16$), $F = 36.715$, $p < .001$, $\eta_p^2 = 0.347$, and then the 11-12 year group ($M_{diff} = 6.58 \mu V^2$, $SD = 3.87$), $F = 5.825$, $p = .020$, $\eta_p^2 = 0.124$. See Figure 1.

Frontal alpha power showed a main effect of Age, $F = 3.681$, $p = .027$, $\eta_p^2 = 0.040$, with planned contrasts indicating that the 9-10 year group ($M = 27.53 \mu V^2$, $SD = 13.36$, 95% CI [25.22, 29.84]) was increased ($p = .010$, Cohen's $d = 0.38$) compared to the 7-8 year group ($M = 23.18 \mu V^2$, $SD = 9.37$, 95% CI [20.86, 25.51]) and no difference between the 7-8 year group and the 11-12 year group ($M = 24.14 \mu V^2$, $SD = 9.18$, 95% CI [21.16, 27.12]). A main effect of Condition indicated reduced power in the EO ($M = 20.28 \mu V^2$, $SD = 8.50$, 95% CI [18.89, 21.66]) compared to the EC ($M = 29.28 \mu V^2$, $SD = 12.78$, 95% CI [27.66, 31.59]) condition, $F = 121.259$, $p < .001$, $\eta_p^2 = 0.405$. There was a significant interaction between Condition and Age, $F = 5.588$, $p = .004$, $\eta_p^2 = 0.059$, with simple effects revealing the largest reduction in the 11-12 year group ($M_{diff} = 12.25 \mu V^2$, $SD = 6.59$), $F = 46.936$, $p < .001$, $\eta_p^2 = 0.534$, followed by the 9-10 year group ($M_{diff} = 10.25 \mu V^2$, $SD = 3.95$), $F = 54.554$, $p < .001$, $\eta_p^2 = 0.442$, and then the 7-8 year group ($M_{diff} = 5.54 \mu V^2$, $SD = 2.31$), $F = 20.165$, $p < .001$, $\eta_p^2 = 0.229$. See Figure 1.

Frontal beta power showed a main effect of Age, $F = 3.390$, $p = .036$, $\eta_p^2 = 0.037$, with planned contrasts indicating that the 7-8 year group ($M = 9.22 \mu V^2$, $SD = 6.00$, 95% CI [8.07, 10.37]) did not differ from the 9-10 year group ($M = 10.11 \mu V^2$, $SD = 6.01$, 95% CI [8.97, 11.25]) or the 11-12 year ($M = 7.65 \mu V^2$, $SD = 3.55$, 95% CI [6.18, 9.12]) group. A follow-up difference contrast confirmed a significant ($p = .019$, Hedges' $g = 0.38$) reduction in beta power in the 11-12 year group compared to the mean of the 7-8 and 9-10 year groups. A main effect of Condition indicated increased power in the EO ($M = 10.98 \mu V^2$, $SD = 7.52$, 95% CI [9.75, 12.22]) condition compared to the EC ($M = 7.00 \mu V^2$, $SD = 2.85$, 95% CI [6.56, 7.44]) condition, $F = 47.010$, $p < .001$, $\eta_p^2 = 0.209$. See Figure 2. The Condition by Age interaction was not significant.

Frontal EO versus FO effects

For both frontal delta and theta power there were no significant Age or Condition main effects or Age by Condition interactions.

Frontal alpha power showed a borderline significant main effect of Age, $F = 3.043$, $p = .050$, $\eta_p^2 = 0.033$, with planned contrasts indicating that the 7-8 year group ($M = 21.01 \mu V^2$, $SD = 15.37$, 95% CI [18.38,

23.64]) did not differ from the 9-10 year group ($M = 22.45 \mu V^2$, $SD = 12.23$, 95% CI [19.83, 25.08]) or the 11-12 year ($M = 17.14 \mu V^2$, $SD = 7.27$, 95% CI [13.74, 20.53]) group. A follow-up difference contrast confirmed a significant ($p = .020$, Hedges' $g = 0.41$) reduction in alpha power in the 11-12 year group compared to the mean of the 7-8 and 9-10 year groups. The Condition main effect and Condition by Age interaction were not significant.

Frontal beta power did not show a main effect of Age. A significant main effect of Condition indicated increased power in the FO ($M = 12.76 \mu V^2$, $SD = 11.81$, 95% CI [10.88, 14.65]) compared to the EO ($M = 10.98 \mu V^2$, $SD = 7.50$, 95% CI [9.74, 12.21]) condition, $F = 7.531$, $p = .007$, $\eta_p^2 = 0.040$. See Figure 2. The Condition by Age interaction was not significant.

Correlations between frontal EC alpha and alpha activation

The correlation between frontal alpha power frontal in the EC condition and alpha activation was significant in the 7-8 year group, $r = -.604$, $p < .01$, $R^2 = .364$, the 9-10 year group, $r = -.675$, $p < .01$, $R^2 = .455$, and the 11-12 year group, $r = -.883$, $p < .01$, $R^2 = .780$.

Follow-up analyses

Additional analyses were conducted to consider the Conditions effects at the individual level. A difference score was calculated by subtracting EEG power in the EC from EO condition for those bands that showed significant Condition effects (i.e. each band). Similarly, a difference score was calculated by subtracting EEG power in the EO from FO condition for those bands that showed significant Condition effects (i.e. the beta band). Table 1 shows the percentage of the overall sample that showed reduced power in the delta, theta, and alpha bands, and increased power in the beta band for the EO-EC values, and showed increased power in the beta band for the FO-EO values. Figure 3 shows histograms of the difference scores.

Discussion

The current study aimed to replicate previously reported EEG activation effects in children using frontal, single-channel, dry-sensor EEG, extend current understanding of frontal arousal and activation by considering age effects in a large sample of children, and explore how top-down attentional activation is reflected in the frontal EEG of children. The sample of children had no current or previous diagnoses of any psychological or psychiatric disorder and showed very low levels of inattentive and hyperactive/impulsive behaviour, and hence can be considered typically-developing.

The activation data were obtained from a frontal scalp location using a single-channel, dry-sensor EEG recording device and replicate previous frontal activation effects in this age-range for delta, theta, alpha, and beta power. This includes eyes-closed to open reductions in alpha power that were global, reductions in delta and theta power reported to vary topographically and be present frontally in children¹⁰, young adults⁴,

and older adults ⁵. The eyes-closed to open increase in beta power in the frontal region has also been reported in children ¹⁰ and young adults ⁴, but not older adults ⁵.

The data presented here extends previous research to consider age effects on frontal EEG in the 7-12 year age-range. The frontal proxy index of arousal did show an effect of age, but the trend was not linear. Given the inverse relationship between alpha power and arousal ⁴, this effect indicates that the youngest and oldest children showed higher resting arousal than the 9-10 year old children as measured with frontal EEG. Consideration of the pattern of means shows a large increase (decrease in resting arousal) in frontal alpha power from 7-8 to 9-10 years and only a minor reduction power from 9-10 to 11-12 years, may suggest a plateau in development over the age-range of the two older groups, although this cannot be confirmed without extending the sample to consider adolescents. Our index of arousal is different to the traditional approach and is thus referred to as a proxy index, as we have utilised only the frontal aspect of the previously established across-scalp global reduction in alpha power in eyes-open compared to eyes-closed conditions and not corroborated or correlated this effect with SCL. Despite this limitation, our protocol facilitated a large sample and provides insight into frontal developmental change in the child age-range.

Our results indicate that frontal EEG indices of activation show substantial developmental change in children. Frontal delta and theta activation effects both reduced as age increased. Thus, frontal EEG power in the lower frequency bands becomes more similar in these two resting conditions as age increases in children. While developmental change appears to be occurring in these EEG bands for both the EC and EO conditions, Figure 1 indicates that the change is larger in the EC condition – thus, the developmental effects may be driven more by changes in neural activity during a resting state with no visual information processing than during basic visual processing. Frontal alpha activation increased as age increased. Thus, frontal EEG power in the alpha band becomes more different in these two resting conditions as age increases in children. These findings indicate substantial developmental change in the frontal aspect of the alpha activation related to bottom-up visual system activity ¹⁵⁻¹⁷; it is not clear if the developmental change is driven primarily by differences in the EC or EO condition. Note that similar activation effects derived from 19-channels of EEG and examined topographically were reported to be unrelated to age in a small sample of children 8 to 12 years old with a mean age of 10.6 years ¹⁰. Thus, the current study has added to our current understanding of developmental change in these indices of activation, with a frontal focus. It would be informative to consider the effect of age from a multi-channel topographic perspective in future research.

In line with the previously-reported multi-channel effects ¹⁰, frontal beta activation did not change as a function of age. An increase in frontal beta power upon opening the eyes characterised bottom-up activation consistently across the 7 to 12 year age-range. This finding appears consistent with functional understanding of frontal activity in this frequency range, which is associated with cognitive engagement and stimulus assessment ^{45,46}.

Attentional activation was seen in an increase in frontal beta power, with no significant differences between the EO and FO conditions for the other EEG bands frontally. The frontal beta activation effect was consistent across the 7 to 12 year age-range. Using the current methodology, which aimed to elicit top-down

attention modulation independently of task-related cognitive/response demands, it is not possible to determine the extent to which children were able to modulate their attention level as instructed in the focus task, although the change in the beta band previously linked functionally to stimulus assessment may indicate they were, to a certain degree, able to complete the task as requested. The frontal beta effects for activation and attentional activation were similarly represented by increased power and no developmental change. In this way, an increase in frontal beta power appears to be common to both bottom-up *and* top-down activation¹⁹.

For each age group, children with lower frontal alpha power in the EC condition showed larger frontal alpha activation; the correlation increased with increasing age. Global alpha activation/reactivity has been interpreted as evidence that the alpha change is mainly due to an arousal increase, due to changes that support visual processing⁵. Our results suggest that this effect is measurable using a single frontal channel, and consistent in children. Future research could incorporate SCL as the “gold standard” measure of arousal to more accurately quantify and corroborate the frontal EEG indices of arousal. Decreased localised delta and theta in the EO condition has been seen as indicative of increased activation associated with unstructured visual processing of the immediate environment in the absence of a task⁵. Though localised, these effects were present frontally in previous studies^{4,5,10}, and were measurable here using a single frontal channel with evidence of developmental change in children.

While the frontal alpha results reported here have been considered in an arousal/activation context, alpha activity has also been explained as cortical inhibition⁴⁷⁻⁴⁹. In this context, an alpha increase indicates that the measured region is more inhibited, whereas an alpha decrease indicates that the measured region is released from inhibition⁴⁸. The inhibition explanation is based on observations that alpha activity is increased in task-irrelevant cortical regions⁵⁰⁻⁵². From this perspective, the frontal alpha activation effect can be explained in terms of a release from cortical inhibition in this region, moving into a more active mode with visual stimulus input. Correspondingly, the developmental pattern reported here for the frontal alpha activation effect suggests that the extent to which the frontal region is less inhibited (more engaged) upon opening the eyes increases with age.

The current replication of previous activation effects derived from multi-channel, research-grade EEG systems in laboratory environments provides further evidence for the validity of frontal, single-channel, dry-sensor EEG. The EC and EO absolute band power values reported here were broadly similar to those previously reported in the frontal region in 8-12 year old children¹⁰, and also independently reported frontal EC absolute power band values in children¹¹. The activation effects showed consistency at the individual level as shown in the distributions of the effects (Figure 3), with the lowest prevalence for beta at 76% and the highest for alpha at 85%. Prevalence of attentional activation was lower, at 58% for beta. While likely influenced by electrophysiological individual differences, this consistency is also dependent on the extent to which children are able to understand the EEG task instructions and carry out the tasks as instructed. As the prevalence rates differed between age groups, developing age-specific instructions may help children more fully understand the task and do their best to complete it as instructed. As it was observed that younger

children sometimes experienced difficulty staying on-task for the full 2 minutes of the EO and EC tasks, dividing the tasks into two 1-minute blocks may be beneficial.

Our data processing approach attempted to address limitations that have been raised about accounting for artifacts when recording from one electrode^{26,27}. In this study, we used the ITMS method⁴⁴ to estimate and suppress the artifact derived from eye-blinks, however, it is plausible that the EEG is affected by some degree of electromyogram (EMG) activity such as eye movements, as well as frontalis and temporalis muscle contractions. Strong EMG activity can cause an overestimation of power at the higher-frequency bands, i.e. beta, and to some extent, alpha⁵³; thus adding extra variability to the measures. Due to the lack of a source signal of EMG activity⁵⁴, attenuating EMG artifact in single-channel EEG applications is challenging. Gasser et al.⁵³ proposed a method in which the power in a higher-frequency band (e.g. 51-69 Hz) was used as an indirect estimate of EMG activity, and used this parameter as a predictor in a regression analysis. The authors of that study demonstrated that the proposed method efficiently corrected the artifact derived from EMG activity in subjects with pre-senile and senile Alzheimer Disease. Taking these results into account, we recommend the use of the EMG correction method proposed by Gasser et al.⁵³ when evaluating subjects with any psychological or psychiatric disorder.

The limitations of recording EEG from only one frontal channel must be acknowledged. As well as presenting challenges for controlling for inevitable blink/eye movement related artifacts, single-channel data does not allow concurrent consideration of data from other brain regions. While these limitations would be insurmountable in certain contexts (e.g. for neurological examination), if the data can be shown to be valid and reliable and replicate known effects derived from research grade EEG systems (as is the case in the present study), they may represent an acceptable trade-off and facilitate EEG recording for certain purposes outside of the laboratory context. For example, in addition to current use in hospital and therapeutic settings, frontal EEG recorded in this manner could provide an additional neurophysiological perspective in the clinical psychological domain or for screening purposes in a medical context. Given the value of resting-state EEG as a biomarker in psychological disorders⁵⁵ and its sensitivity to developmental change¹⁴, the ability to record frontal EEG in a clinic setting in a convenient, technically simple, and low-cost manner could be very valuable. This EEG could inform the diagnostic process or provide an objective physiological index of treatment suitability, progression, or outcome. To realise such clinical potential the characteristics of the frontal EEG must be established through systematic research (as represented here), alongside the development of large-scale normative and clinical databases for comparisons of individual EEG profiles. The value of such an approach that utilises mobile EEG, thus facilitating large-scale EEG data collection, has been recently recognised^{38,56}.

These results presented here should be considered in light of several limitations. While the sample of children did not have any current or previous diagnoses of any psychological or psychiatric disorder and showed very low levels of inattentive and hyperactive/impulsive behaviour, we did not assess their basic cognitive functioning (e.g. as indicated by IQ) or learning ability. We have used as our measure power spectral density, which is typically a decreasing function with lower power at higher frequencies, XX.

Although the ANOVA is robust to different participant numbers in between-group comparisons⁵⁷, the smaller sample in the 11-12 year group may have affected the results. As mentioned above, we did not record SCL to confirm its relationship with eyes-closed resting alpha as a measure of arousal. The focus task was designed to be relatively free of task-related requirements and cognitive processing, and used a slowly morphing stimulus based on our pilot studies which showed that children reported that modulating attention in the absence of a stimulus or with just a simple shape stimulus (e.g. a blue square) difficult. While the children had no instructions related to the morphing shape stimulus, and were instructed only to “focus hard on the screen” putting emphasis on top-down attention modulation, the attentional activation effect may be at least partly due to the visual processing element.

Conclusions

The current study has replicated the frontal findings of previously reported EEG activation effects in children aged 7 to 12 years using frontal, single-channel, dry-sensor EEG. These findings contribute further to validation of the single-channel, dry-sensor, frontal EEG. Further, this study has extended current understanding of EEG activation effects to reveal developmental change for frontal delta, theta, and alpha activation and stability frontal beta activation across the 7 to 12 year age-range. We reported non-linear developmental change in a frontal proxy index of arousal. The exploration of top-down attentional activation revealed that it was characterised by an increase in frontal beta power only, with stability across the 7 to 12 year age-range. Future research could investigate the consistency of these findings in children from a western culture. Further, in line with the framework of the CEM, future studies might consider the relationship of arousal, activation, and attentional activation to cognitive/executive function performance, and consider these effects in children with neurodevelopmental disorders such as ASD or AD/HD.

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Declaration of conflicting interests

The Authors declare that there is no conflict of interest.

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Table 1. Significance Values for the Main Effects and Interactions for the Activation (EO-EC) and Attentional Activation (FO-EO) Analyses.

Condition	Band	Age main effect			Condition main effect			Age × condition interaction		
		<i>F</i>	<i>P</i>	η_p^2	<i>F</i>	<i>P</i>	η_p^2	<i>F</i>	<i>P</i>	η_p^2
EO-EC	Delta	2.962	.054	0.032	59.231	.001	0.250	4.098	.018	0.044
	Theta	6.535	.002	0.067	47.768	.001	0.212	3.236	.042	0.035
	Alpha	3.681	.027	0.040	121.259	.001	0.405	5.588	.004	0.059
	Beta	3.390	.036	0.037	47.010	.001	0.209			
FO-EO	Delta									
	Theta									
	Alpha	3.043	.050	0.033						
	Beta				7.531	.007	0.040			

Abbreviations: EC, eyes closed; EO, eyes open; FO, focus.

Table 2. Percentage of Participants Who Showed Change in the Expected Direction for the Significant Condition Effects, for Each Age Group Separately.

Condition	Band	7-8 years	9-10 years	11-12 years	Mean
EO-EC	Delta	87.3	81.4	75.0	81.2
	Theta	85.7	81.4	73.8	80.3
	Alpha	73.5	87.1	95.2	85.3
	Beta	77.3	79.1	72.2	76.2
FO-EO	Beta	60.9	67.2	46.2	58.1

Abbreviations: EC, eyes closed; EO, eyes open; FO, focus.

Figure 1. The condition by age interactions for frontal delta, theta, and alpha power. Error bars show standard error. EC, eyes closed; EO, eyes open.

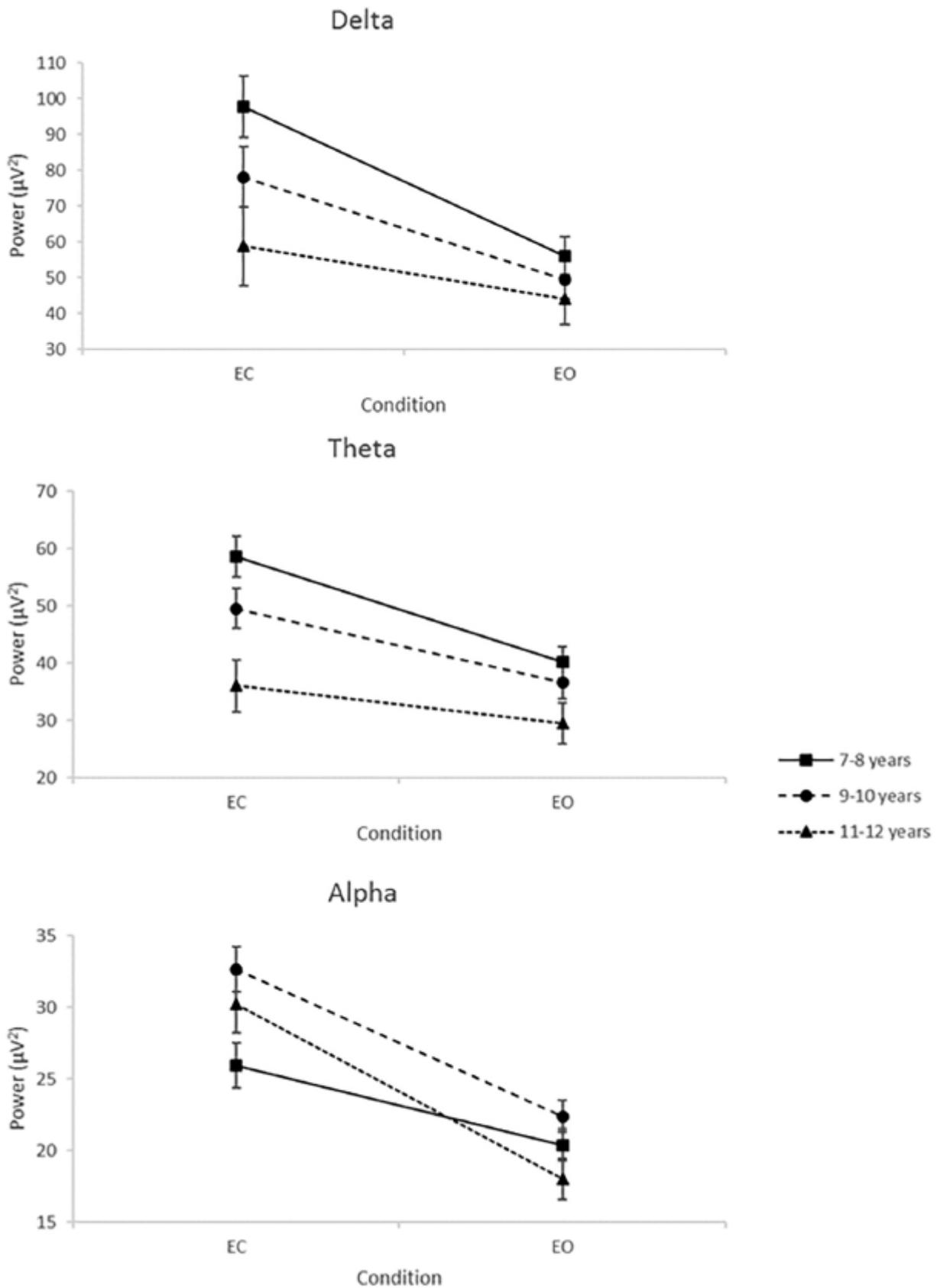


Figure 2. The condition main effects for frontal beta activation and frontal beta attentional activation. Error bars show standard error. The activation comparison involved quantification of the full 120-second trace for the EC and EO conditions. The attentional activation comparison involved quantification of a randomly chosen 60-seconds trace from the EO condition and the 60-second trace of the FO condition. EC, eyes closed; EO, eyes open; FO, focus.

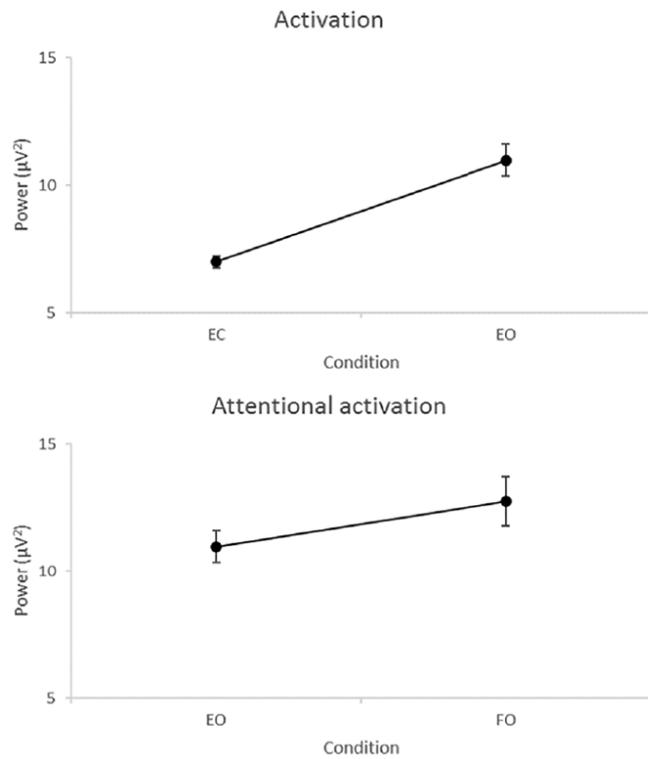


Figure 3. Histograms of the EO-EC (top 4 panels) and FO-EO (lower panel) difference scores (in $\mu\text{V}2$). Values less than zero indicate an effect in the direction of the condition effects for delta, theta, and alpha activation. Values greater than zero indicate an effect in the direction of the condition effects for beta activation and beta attentional activation. EC, eyes closed; EO, eyes open; FO, focus.

