

Children's EEG Indices of Directed Attention during Somatosensory Anticipation: Relations with Executive Function

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Abstract

Children's ability to direct attention to salient stimuli is a key aspect of cognitive functioning. Here we examined the magnitude and lateralization of EEG indices during somatosensory anticipation elicited by a left or right directional cue indicating the bodily location of an upcoming tactile stimulus. In 50 children aged 6-8 years, somatosensory anticipation was accompanied by anticipatory negativity and alpha mu rhythm desynchronization at contralateral central electrode sites (C3 and C4) overlying the hand area of the somatosensory cortex. Individual differences in these contralateral brain responses during somatosensory anticipation were associated with scores on a flanker task of executive function. The results suggest that processes involved in directing attention in the tactile modality may overlap with those involved in broader executive function abilities.

Introduction

The ability to direct attention in a focused and efficient manner is crucial to cognitive performance and decision-making (Posner and Fan, 2008). Directed attention is the heightened monitoring of spatial location prior to presentation of a target stimulus, and is known to facilitate heightened perception, shorter reaction time and improved inhibition in adults (Rothbart, Posner and Kieras, 2006). Introduction of preparatory cues relevant for upcoming target stimuli allows study of neural activity or behavior during *anticipation*, prior to subsequent attention and perception of stimuli (Anderson and Ding, 2012). Anticipation is the goal-directed monitoring of sensation in expectation of a stimulus. Within a sensorimotor contingency framework, anticipatory brain responses can be viewed as 'pragmatic' in that they prepare for expected action (Engel et al., 2013), reflecting the reciprocal nature of prior experience, cognition and action (O'Reagen, 2011). In directed attention tasks with children, individual differences in post-stimulus neural activity to target stimuli (Stevens and Bavelier, 2012) are associated with cognitive skills and school achievement, but pre-stimulus anticipatory neural activity is rarely examined as an index of cognitive ability.

Directed attention paradigms investigate how manipulation of endogenous (top-down) attention facilitates subsequent exogenous (bottom-up) stimuli-driven attention, perception, and neural responses to target stimuli. Neural activity in the region that encodes target stimuli features are

modulated not only in response to stimuli, but also during anticipation (Corbetta and Shulman, 20012). This effect is present even when the preparatory cue is presented in a different sensory modality from that of the expected target, allowing temporal and spatial differentiation of anticipatory activity in the target sensory cortex from cue encoding (Zanto and Gazzley, 2009). During anticipatory attention, preparatory cues uniquely engage the intra-parietal sulcus (IPS) to apply a filter on attention, which is not active in subsequent target perception (Corbetta and Shulman, 2002).

Emerging research accounts for neural activity unique to anticipation as filtering the focus of attention in expectation of an upcoming target (Zhang and Ding, 2010). To examine this account, we study how the magnitude of anticipatory neural activity during a somatosensory directed attention task relates to performance on the flanker task, which demands conflict monitoring, or a focus on single target stimuli among distractors competing for attention (Rothbart, Posner and Kieras, 2006). The flanker task requires participants to respond to the direction of a central target arrow amidst congruent or incongruent flanking distractor arrows: incongruent conditions are associated with slower reaction times, explained as resolving the conflict between the target and distractors. The flanker task taps into endogenous attentional abilities measured by executive function (EF). Our understanding of EF is informed by relational-systems theory, with EF defined as the goal-directed regulation of behavior, aligning action with top-down attention (Dick and Overton, 2011). We are concerned with the relations between flanker task performance and individual differences in the neural indices during somatosensory anticipation, elicited in a directed attention paradigm in which a visual cue directs children's attention to the expected spatial location of an upcoming tactile stimulus. Associating neural indices of somatosensory anticipation with EF facilitates study of inter-sensory attention, with potential for linking sensory-specific attentional processes to cognitive skills.

EEG Indices of Somatosensory Anticipatory Attention

Changes in brain responses recorded through the *electroencephalogram* (EEG) are reliable indicators of attention orienting, sometimes proving more predictive of relevant behavior than reaction time responses to stimuli (Foxe and Snyder, 2011). Brain responses to directed

attention are lateralized, such that there is a modulation of neural activity contralateral to the direction of the spatial cue (Gazzaley and Nobre, 2012). Attention can be indexed by the modulation of EEG signals in the alpha band (8-14 Hz in adults). Alpha band fluctuations are interpreted as a correlate of underlying attentional states, with the magnitude of change in amplitude sensitive to stimuli salience, strength and individual differences. When monitoring stimuli presented to one visual field, to one hand or to one ear, there is typically a disruption of rhythmic alpha activity known as *event-related desynchronization* (ERD) in the contralateral sensory cortex (Stevens and Bavelier, 2012). Desynchronization of the alpha rhythm appears to reflect an increase in local field potentials of neurons in the region of interest. Heightened alpha band desynchronization is thought to increase the perceptual salience of upcoming stimuli in the target modality (Foxe and Snyder, 2011). In the tactile modality, anticipatory desynchronization of the alpha-range mu rhythm at central electrodes is an index of somatosensory cortex excitability.

Attention-related changes in the EEG during anticipation can also be indexed via *event-related potential* (ERP) methods. Relevant here is the contingent negative variation (CNV), a negative-going potential occurring during the anticipatory period between a preparatory cue and a target stimulus (Corbetta and Shulman, 2002). The CNV elicited by a preparatory cue can be considered to reflect endogenous anticipatory directed attention, while later potentials (P1, N2, P3) can be considered to reflect exogenous, stimulus-evoked attention.

There is an emerging literature studying pre-stimulus EEG activity during the anticipation of touch. Detection of weak tactile stimuli was predicted by contralateral power of anticipatory alpha desynchronization (Zhang and Ding, 2010) after a cue indicated upcoming stimulation of the right hand. Anticipatory somatosensory selective attention paradigms often include a cue containing relevant spatial information about upcoming tactile stimulation, to examine the lateralization of brain responses or hemispheric asymmetry. Haegens, Luthur and Jensen (2012) demonstrated anticipatory desynchronization of alpha rhythm in central electrodes contralateral to the direction of the spatial cue, and synchronization of the alpha rhythm in the ipsilateral central electrodes. To our knowledge, there is no existing research on the cognitive mechanisms facilitating the association of pre-stimulus alpha mu desynchronization and post-stimulus enhanced perception of tactile stimuli. There are also no studies on the developmental trajectory of neural indices during somatosensory anticipation.

Development of Directed Attention and EF

Precursors to attention regulation are apparent in infancy, with gaze fixation sensitive to stimulus features, novelty preferences, and prior learning in newborns (Hood, Willen, Driver, 1998; Sheese et al., 2008). Goldberg, Maurer and

Lewis (2001) found age-related differences in children's target discrimination on visual selective attention paradigms when target and non-target stimuli were presented simultaneously. By age 8 years, performance was comparable to adults in anticipatory visual selective attention tasks. The authors suggested discrepant trajectories in the development of distractibility and anticipation.

There is interest in studying the neural indices elicited by selective attention, when distractors presented simultaneous to the target compete for directed attention. Coch, Sanders and Neville (2005) employed a dichotic listening task to examine neural indices in response to target tones in attended and unattended simultaneous auditory streams in children aged 6-8. They found a slow positive ERP peaking around 150 ms in children as opposed to the typical ERPs found in adults: early sensory potentials, followed by an N2 and P3. The amplitude of the ERP was greater in the attended auditory stream than the unattended auditory stream. Isbell, Wray and Neville (2015) found the positivity of auditory-evoked selective attention potentials related to non-verbal IQ scores, such that only higher-IQs preschoolers exhibited significant differences in amplitude distinguishing target tones in the attended stream from tones in the unattended stream. The nature of the dichotic listening task requires the same skills as the tasks involved in non-verbal IQ assessment. A study of anticipatory attention to visual stimuli in 10-year-old children found that CNV magnitude (evoked by preparatory spatial cues) related to visual short-term memory capacity (Shimi et al., 2014). The measure of EF was response to the targets of 'anticipatory attention', so it is difficult to tease apart the relations among task performance, working memory and neural indices of attention.

Prior studies suggest adult executive function relates to brain responses during attention to visual or auditory stimuli. During a dichotic listening task, the amplitude of the contralateral brain responses during auditory selective attention relates to non-verbal working memory (Giuliano et al., 2014). In contrast, a study of visual selective attention found only ipsilateral brain responses to be related to cognitive skills (Zanto & Gazzaley, 2009). The authors found that the ipsilateral increase in amplitude accounted for greater variation in working memory, when compared to the magnitude typically associated with selective attention, which is reduced alpha power in the contralateral occipital cortex. The current investigation extends the study of anticipatory attention and cognitive skills to the somatosensory domain by examining how EF relates with EEG indices of directed attention to upcoming tactile stimuli.

Current Study

Studying pre-stimulus attention in the tactile modality contributes to the basic science of bodily awareness and somatosensation. The fundamental, early-developing nature of somatosensory processing (Marshall & Meltzoff, 2015) make it a compelling domain of study for examining the

development of top-down attentional processes. Furthermore, perception of tactile pulses appears uniquely associated with neural indices of attention, unlike reaction time in response to tactile pulses (Zhang and Ding, 2010): Electrophysiological data can therefore provide insight into the perception of touch, beyond simultaneous behavioral measures. Our study examines how the somatosensory domain adds to the developmental literature on executive function indices of domain-general attention.

The current study examined the magnitude and lateralization of CNV potentials and sensorimotor alpha mu rhythm modulation, as elicited by a directional cue indicating the bodily location of upcoming tactile stimuli. We hypothesized that individual differences in brain responses during somatosensory anticipation would be associated with scores on a flanker task. This potential association between the cognitive state elicited during anticipation and EF was the key focus of the study.

Methods

Participants

Sixty children between the ages six to eight years of age participated in the study ($M = 7.2$ years, $SD = .6$; 27 male). Families were recruited from a diverse urban environment using commercially available mailing lists and online advertisements. Families were not invited to participate if their child had any medical or psychological diagnoses, was left-handed, or on any long-term medication. A number of children were excluded from analyses because they did not have a sufficient number of artifact-free trials ($n = 6$) or because the child did not tolerate cap preparation ($n=4$). These 10 excluded children did not statistically differ in scores on the flanker from the remaining sample ($N=50$).

Procedure

Children were read an assent form outlining the protocol in the presence of their caregiver, who also read the consent forms. Children were then fitted with an EEG cap while seated at a table facing a computer screen, with instructions to stay as still as possible with their hands on their lap, out of sight. Research assistants explained the paradigm as a game that required children to pay close attention to the right or left hand, as indicated by the arrow, and respond to the tactile stimuli by pressing a foot pedal once if they felt one tap or twice if they felt two taps. Each of the 120 trials began with a fixation cross baseline for 1500 ms, followed by an arrow displayed for 500 ms, followed by a response screen which read ‘Copy with Your Foot!’ (Figure 1).



Figure 1. Protocol consisted of 120 trials: a 1500 ms baseline, then an arrow displayed for 500 ms, then tactile stimuli and response.

Tactile stimulation was delivered using a pneumatic simulator controlled by STIM stimulus presentation software (both device and software from James Long Company), with the compressed air delivered during the arrow display and before the response screen. An inflatable membrane mounted in a plastic casing was placed on the middle fingers of children’s left and right hands, held in place by a finger clip. The membrane is inflated by a short burst of compressed air delivered via flexible polyurethane tubing (3 m length, 3.2 mm outer diameter). The tactile stimulus feels like a light tap on the finger, lasts around 60 ms, and has a peak force of around 2 N.

The NIH Cognition Toolbox flanker task was then administered. Children completed the flanker task on an iPad by selecting the direction of a central target arrow among 4 flanking distractor arrows, which were either congruent or incongruent in direction to the target arrow. Scores were calculated as number of trials with correct response for incongruent trials weighted by reaction time, such that a higher score indicated better EF abilities.

EEG Collection and Processing

EEG was recorded using a 32-electrode stretch cap (ANT Neuro, Inc.) from the following sites: Fp1, Fpz, Fp2, F3, F4, Fz, F7, F8, C3, C4, CP1, CP2, T7, T8, P3, P4, Pz, P7, P8, O1, Oz, O2, and the left and right mastoids. Conducting gel was used and scalp electrode impedances were kept under 25 k Ω . The signal from each site was amplified using optically isolated, high input impedance (> 1 G Ω) custom bioamplifiers (SA Instrumentation) and was digitized using a 16-bit A/D converter (± 5 V input range). Bioamplifier gain was 4000 and the hardware filter (12 dB/octave rolloff) settings were .1 Hz (high-pass) and 100 Hz (low-pass). EEG analysis was performed using the EEGLAB 13.5.4b toolbox (Delorme and Makeig, 2004) implemented in MATLAB. The signal was collected referenced to the vertex (Cz), and EEG signals were re-referenced offline to an average mastoids reference for further analysis. Independent component analysis (ICA) cleared EEG data of ocular and muscle artifact. The ICA procedure was an automation of the method described by Hoffmann & Falkenstein (2008). Visual inspection of the EEG signal was then used to reject epochs containing movement artifact. The mean number of artifact-free trials per cue direction was 41 ($SD = 5.71$).

Results

Analyses focused on electrode sites overlying the hand area (the left and right central electrodes; C3 and C4) of sensorimotor cortex. For all ANOVAs, within-subject effects were adjusted using Greenhouse-Geisser correction factors; pairwise t-test comparisons and multiple linear regressions were reported with p-values adjusted for multiple comparisons.

Anticipatory Negativity

We extracted mean amplitude during the 300 ms immediately preceding tactile stimulation, within the 500 ms window relevant to anticipatory attention. This window

was selected to study the CNV waveform, accounting for a 200 ms delay after the preparatory cue (Shen et al., 2017).

To study lateralization of anticipatory negativity, an ANOVA compared mean CNV amplitude by electrode (C3 or C4) and cue direction (left or right arrow). There was a significant main effect of cue direction, such that cues directing attention to the right hand elicited an enhanced anticipatory negativity ($F(1, 48) = 37.06, p < .019$). There was a significant main effect of electrode, such that C3 exhibited enhanced anticipatory negativity ($F(1, 48) = 37.06, p < .001$). As expected, there was significant interaction between electrode (C3 or C4) and cue direction, $F(1, 48) = 15.95, p < .001$, driven by negativity in the electrode contralateral to the stimuli: pairwise comparisons (adjusted with FDR) reveal amplitude in C3 was lower for right cue than left cue, $p < .001$, while the opposite trend was found for the amplitude of C4, $p < .061$ (see figure 2).

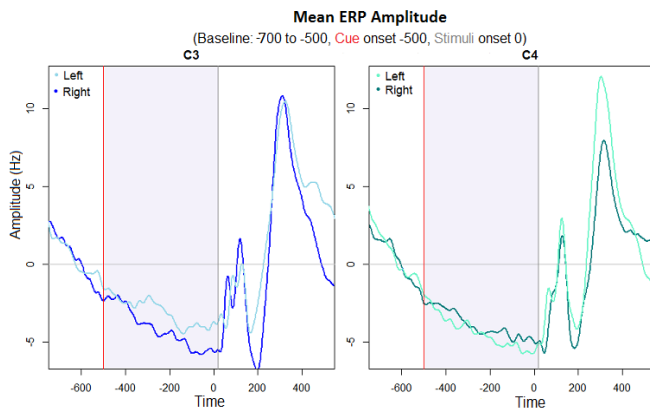


Figure 2. For each trial, an epoch of 1500ms was extracted: analyses focused on the 300ms preceding tactile stimulation during the pre-stimulus period, accounting for the average amplitude during a pre-cue 200-ms baseline. The epochs were then filtered at 30 Hz.

Anticipatory ERPs and Flanker. To examine the relations between flanker and anticipatory negativity, regressions were conducted predicting flanker scores from lateralization of CNV amplitude and its interactions with electrode and cue direction. We computed lateralization of CNV amplitude by subtracting the mean amplitude at C3 from mean amplitude at C4, for each participant and each hand. There was a trend of lateralized amplitude predicting flanker score, $t(1, 48) = 1.72, p = .090$. Performance on the flanker task was predicted by a significant interaction between lateralized amplitude and cue direction, $t(1, 48) = -2.40, p = .019$. To further probe this interaction, we performed post-hoc regressions predicting flanker score by average amplitude for C3 and C4 during right and left cues. The interaction was driven by marginal relations between flanker and amplitude in the contralateral hemisphere: flanker score related with CNV amplitude over C3 elicited by a right directional cue, $t(1, 49) = -1.72, p = .094$, and over C4 elicited by a left directional cue, $t(1, 49) = -1.70, p = .097$. Amplitude in the ipsilateral hemisphere did not relate with flanker score.

Time Frequency Analysis

Event-related spectral perturbation (ERSP) analyses were conducted on the alpha frequency band at 7–12 Hz (Berchicci et al., 2011; Marshall, Bar-Haim, & Fox, 2002), as is appropriate for children, and baseline corrected for the 500 ms prior to cue onset. Event-related desynchronization (ERD) is as an alpha power decrease relative to the baseline. An ANOVA compared pre-stimulus alpha power by electrode (C3 or C4) and cue direction (left or right arrow). There was a main effect of cue direction, such that cues directing attention to the right hand elicited greater desynchronization, $F(1, 48) = 37.06, p < .001$. There was no main effect of electrode position. A significant interaction was observed between electrode and cue direction, $F(1, 48) = 15.95, p < .001$ (see figure 3). The interaction was due to greater ERD in the contralateral hemisphere (see figure 4): the mu rhythm showed greater desynchronization over C3 elicited by the right cue, and over C4 elicited by the left cue.

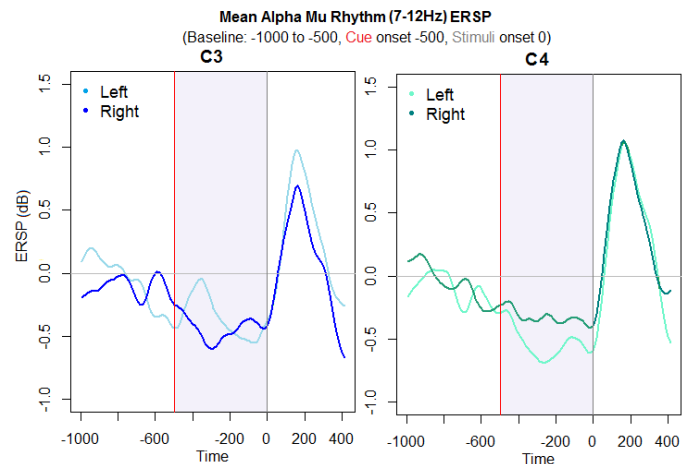


Figure 3. For each trial, an epoch of 1500ms was extracted: spectral power was estimated using Gaussian-tapered Morlet wavelets, and changes in power were computed as ERSP focused on the 500ms pre-stimulus period, relative to a 500 ms baseline (-1000 to -500 ms).

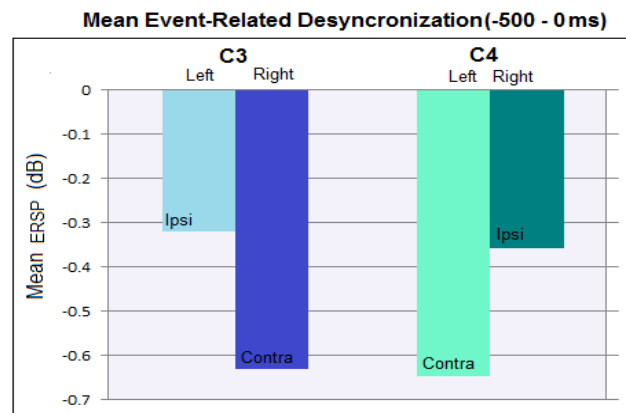


Figure 4. Mean ERSP for mu rhythm (7–12 Hz) in C3/C4 for left/ right cues from -500 ms to 0 ms. Negative values reflect a reduction in mu power (ERD) relative to a 500 ms pre-cue baseline (-1000 to -500 ms).

Anticipatory ERSP and Flanker. To examine the relation of flanker task scores with ERD during somatosensory anticipation, regressions were conducted predicting scores on flanker task by ERD and its interactions with electrode position and cue direction, controlling for within-participant variability. There were no significant main effects or two-way interactions. However, performance on the flanker task was significantly predicted by a three-way interaction between alpha power, electrode position and cue direction, $t(46) = 2.33, p = .012$. Post-hoc regressions (with p -values adjusted for the false discovery rate) further probed the relations, revealing ERD in the hemisphere contralateral to the direction of the cue was inversely related to the scores on the Flanker task: for right cue over C3, $t(1, 49) = -2.65, p = .014$, and for left cue over C4, $t(1, 49) = -2.50, p = .021$. ERD in the ipsilateral hemisphere was not related with flanker score (see Table 1). Refer to Figure 5 for inverse correlations between flanker score and contralateral ERD.

Table 1. Flanker predicted by ERD, Cue, & Electrode

Overall Regression	<i>B</i>	Std Error	<i>t</i> value	<i>p</i>
ERD	-3.51	2.53	-1.39	.16
Electrode	-.627	2.49	-.252	.80
Cue	2.44	2.45	.977	.32
Power*Cue*Electrode	2.33	.021	2.33	.01*
Post-Hoc Regression	<i>B</i>	Std Error	<i>t</i> value	<i>p</i>
Right Cue C3	-3.68	1.39	-2.65	.01*
Right Cue C4	1.70	1.45	1.17	.24
Left Cue C3	1.52	1.20	1.40	.18
Left Cue C4	-6.42	2.56	-2.50	.02*

*Significant at less than $p=.05$; p -values of post-hoc corrected for FDR

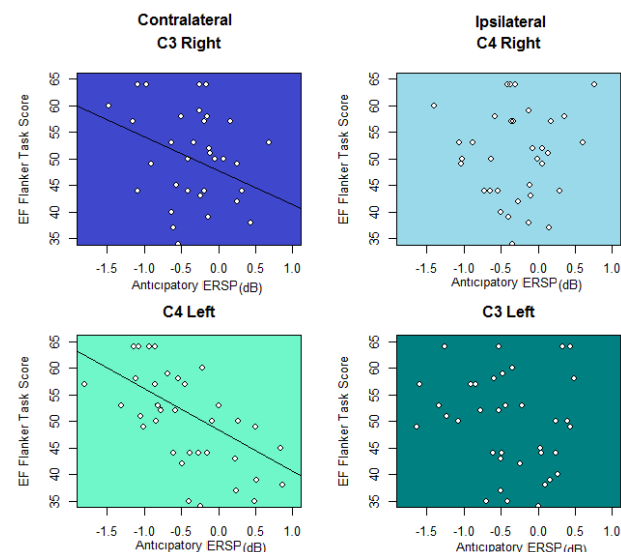


Figure 5. Correlations of Flanker scores with ERD: significant correlations were found for pre-stimulus ERSP contralateral to cue direction. For right cue over C3, $r = -.395$; for left cue over C4, $r = -.377$. There was no relation between flanker scores and ipsilateral ERSP; right cue over C4, $r = .106$; left over C4, $r = -.021$.

Discussion

The current study investigated somatosensory anticipation in children, and if anticipatory EEG responses in amplitude and alpha mu rhythm were related with individual differences in flanker scores. Just as seen in adults, we found a preparatory spatial cue directing attention to the bodily location of upcoming tactile stimulation modulated the activity of the alpha mu rhythm. Children's contralateral alpha band activity (in C3 – Right Cue and C4 – Left Cue) during anticipation was inversely associated with performance on a flanker task, while ipsilateral responses had no relation to flanker scores. Anticipatory negativity (i.e., the CNV response) was lateralized, with more negative amplitudes in the hemisphere contralateral to cue direction. The degree of lateralization, computed as mean amplitude at C4 – C3, was related to participants' flanker scores, which subsequent analyses demonstrated were driven by contralateral negativity. Children's ability to modulate attention in preparation for tactile stimulation appears to be related to individual differences in EF, as codified by their scores on the flanker task.

Our findings of an association between flanker and neural indices of tactile attention should be interpreted with caution, as our sample is small for a study of individual differences. Studies linking neural indices of somatosensory anticipation and attention with other EF tasks should be conducted, to parallel research in other sensory modalities (Isbell, Wray and Neville, 2015). Other studies of anticipation in adults suggest that ipsilateral EEG activity suppresses responses to distractors (Hagens, Luthur, and Jensen, 2012; Zanto & Gazzaley, 2009), but our paradigm did not include distractor stimuli; our study observed only a trending alpha power increase in the ipsilateral hemisphere, elicited by stimuli to the left hand. Further investigations can examine whether introducing simultaneous, competing stimuli in the somatosensory domain elicits an ipsilateral increase in alpha mu rhythm, as observed during anticipatory somatosensory selective attention in adults. A paradigm with simultaneous tactile stimulation to both hands would be more parallel to developmental research on the relations of cognitive skills and children's somatosensory *selective* attention rather than our study of somatosensory *directed* attention. First, we believed it crucial to replicate modulation in EEG indices during the anticipation of tactile stimuli in children, and further investigation is needed to assess how preparatory cues influence anticipation, attention and perception when distractors are introduced. Our results support that shared processes are involved in sensory-specific directed attention and domain-general EF, but continued study of attention in different modalities will address theories of inter-sensory attentional mechanisms (Gazzaley and Nobre, 2012). Study of brain responses to tactile stimuli uniquely informs models of action-oriented representation, wherein internal (cognitive and physiological) states reflect the environment and prescribe action (Clark, 1998; Engel et al., 2013).

Research on bodily awareness and representation would benefit by studying how the associated neural indices of somatosensation are influenced by attention and related cognitive processes. Children's neural indices during directed attention to bodily sensation appear similar to those in adults, when compared to ERP responses evoked during visual and auditory attention (Stevens and Bavelier, 2012). This could be interpreted as signaling the importance of somatosensory attention in development, although further work is needed to establish whether tactile attention is more predictive than attention in other modalities (e.g. vision). Future studies of the neural indices of somatosensory attention could lay the foundation for interventions that train attention or executive function in children.

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