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Attentional Selection and Suppression in Children With Attention-Deficit/Hyperactivity Disorder

Encong Wang, Li Sun, Meirong Sun, Jing Huang, Ye Tao, Xixi Zhao, Zhanliang Wu, Yulong Ding, Daniel P. Newman, Mark A. Bellgrove, Yufeng Wang, and Yan Song

ABSTRACT

BACKGROUND: Attention-deficit/hyperactivity disorder (ADHD) is a prevalent neurodevelopmental disorder with prominent impairments in directing and sustaining attention. The aim of this study was to identify the neurophysiologic bases of attention deficits in ADHD, focusing on electroencephalography markers of attentional selection (posterior contralateral N2 [N2pc]) and suppression (distractor positivity [P_D]).

METHODS: The electroencephalography data were collected from 135 children 9–15 years old with and without ADHD while they searched for a shape target in either the absence (experiment 1) or the presence (experiment 2) of a salient but irrelevant color distractor.

RESULTS: In experiment 1, the shape target elicited a smaller N2pc in children with ADHD ($n = 38$) compared with typically developing children ($n = 36$). The smaller N2pc amplitude predicted higher levels of inattentive symptoms in children with ADHD. Moreover, the target-elicited N2pc was followed by a positivity in typically developing children but not in children with ADHD. In experiment 2, the salient but irrelevant color distractor elicited a smaller P_D component in children with ADHD ($n = 32$) compared with typically developing children ($n = 29$). The smaller P_D predicted higher inattentive symptom severity as well as lower behavioral accuracy in children with ADHD.

CONCLUSIONS: The correlation between N2pc/P_D amplitudes and ADHD symptom severity suggests that these signals of attentional selection and suppression may serve as potential candidates for neurophysiologic markers of ADHD. Our findings provide a neurophysiologic basis for the subjective reports of attention deficits in children with ADHD and highlight the importance of spatial attention impairments in ADHD.

Keywords: ADHD, Electroencephalography, N2pc, P_D, Selection, Suppression

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Attention-deficit/hyperactivity disorder (ADHD) is characterized by developmentally inappropriate symptoms of inattention, hyperactivity, and impulsivity and affects ~5% of school-age children (1). Although the disorder is defined by subjective reports of attention deficits, the nature of any objective impairment of sustained or selective attention remains actively debated. Previous behavioral studies reported that individuals with ADHD had unimpaired selective attention and could effectively use top-down control to filter distracters (2–4). However, a series of electroencephalography (EEG) studies using spatial cuing paradigms found abnormal alterations in posterior alpha and frontal theta activity as well as their functional disconnection in response to a cue in children with ADHD (5–7). Additionally, several previous event-related potential (ERP) studies demonstrated that subjects with ADHD have deficits in both early sensory components (8) and subsequent response selection in some visual spatial tasks (9,10). These EEG and ERP findings imply the possible occurrence of spatial attention impairments in ADHD.

One ERP component known as posterior contralateral N2 (N2pc) is a well-characterized index of covert visual attentional selection (11–13). The presence of a reliable N2pc in response to salient but task-irrelevant visual objects has been interpreted as reflecting stimulus-driven bottom-up attentional capture (14,15), whereas modulation of the N2pc by task set and anticipation has been interpreted as evidence for attentional top-down control (16–22). A hallmark of selective attention is the active suppression of task-irrelevant, distracting information. Another ERP component known as distractor positivity (P_D) is thought to be a neurophysiologic marker of this active suppression mechanism (21–28). This positivity is elicited when selective processing of the eliciting stimulus is to be avoided (22–27) or terminated (21,28).

To the best of our knowledge, neither N2pc nor P_D has been studied in children with ADHD. Yet, *prima facie*, there is good reason to expect that these neurophysiologic markers could relate to the attention deficits of children with ADHD, which include distractibility and problems maintaining attentional focus. One recent study showed that the N2pc delay

may be a neurocognitive endophenotype of adult ADHD (29); however, we cannot tell whether this N2pc pattern developed over the course of the disease or whether it would likewise be observable in children. The present study investigated 1) whether attention problems in children with ADHD could be partly explained by a reduced ability to modulate N2pc, P_D, or both and 2) whether abnormalities in these components were related to symptom severity in children with ADHD. To that end, we conducted two visual search experiments to assess the characteristics of covert visual spatial attentional selection in children with ADHD and their ability to suppress salient but irrelevant distractors.

METHODS AND MATERIALS

Participants

For this study, 170 children (95 with ADHD, 132 boys) were recruited. Written consent was obtained from all children and their parents according to the Declaration of Helsinki. The study was approved by the Ethics Committee of Peking University Institute of Mental Health. Data from 35 participants were discarded because of the high ratio of noise in the EEG signals or excessive horizontal and vertical eye movement (see the Supplement for the objective exclusion criteria). The group comparisons reported here are from the remaining 135 participants (70 with ADHD, 104 boys; 79% of the samples). Specifically, 38 drug-naïve children with ADHD (32 boys) and 36 typically developing (TD) children (27 boys) participated in experiment 1. Participants in experiment 2 were 32 drug-naïve children with ADHD (26 boys) and 29 TD children (19 boys). For both experiments, there were no significant differences between the groups in terms of age, IQ, and sex ratios (Table 1). Diagnosis of ADHD was based on DSM-IV criteria (Supplement).

Search Paradigm

The stimulus was a circular search array, consisting of 12 items positioned around the circle at a distance of 5° visual angle from the central fixation cross (Figure 1A). The stimuli in experiment 1 consisted of one circle (target) and 11 diamonds; experiment 2 consisted of a shape singleton target with a salient but irrelevant color singleton distractor (red or green) simultaneously presented. In both experiments, the tasks remained the same for the participants: participants were instructed to maintain their gaze at fixation and report the position of the target (upper or lower) but to ignore other extraneous items and distractors. The Supplement provides more specific paradigm details.

Table 1. Sample Characteristics in Experiment 1 and Experiment 2

Experiment	Group (*n*)	Age (Years)	Males	FSIQ	ADHD-RS_{inatt}	ADHD-RS_{hyper}
1	ADHD (38)	11.6	32	108	26.9[a]	19.7[a]
	TD (36)	11.2	27	112	12.5	11.2
2	ADHD (32)	12.5	26	110	27.2[a]	20.4[a]
	TD (29)	12.7	19	113	13.3	11.5

ADHD, attention-deficit/hyperactivity disorder; ADHD-RS_{inatt}, inattention subscale of ADHD Rating Scale; ADHD-RS_{hyper}, hyperactivity/impulsivity subscale of ADHD Rating Scale; FSIQ, full scale IQ; TD, typically developing.

[a]$p < .001$ indicates group difference significance.

ERP Recording and Analysis

The EEG data were acquired from 128 channels (HydroCel Geodesic Sensor Net; Electrical Geodesics, Inc., Eugene, OR) with Net Station EEG Software. The impedance of all electrodes was kept below 50 kΩ during the data acquisition. All electrodes were physically referenced to Cz (fixed by the EGI system). The EEG data were amplified with a band pass of 0.01–400 Hz (half-power cutoff) and digitized online at 1000 Hz.

Offline EEG processing and analyses were performed using custom MATLAB (The Mathworks, Inc., Natick, MA) scripts and functions from the EEGLAB environment (30). The EEG data were band-pass filtered (half-power cutoff at 1–40 Hz) with a roll-off of 12 dB/octave (7) and then were re-referenced to the average of the left and right mastoid channels. Electrodes containing excessive artifact or high-amplitude, high-frequency muscle noise (>50% of total recording time) were excluded from further analysis. Data from the task blocks in each experiment were concatenated to form a continuous time series. This time series was subsequently inspected for outlier epochs encompassing gross movements and muscle artifacts, and these time series were removed. The trimmed data were then decomposed into maximally independent component processes using temporal independent component analysis decomposition via extended infomax. The components of independent component analysis associated with vertical eye movements were visually identified and removed according to their spatial, spectral, and temporal properties. The data were then segmented relative to stimulus onset (−200 to 600 ms), and the baseline preceding the stimulus (−200 to 0 ms) was subtracted. Epochs were then sorted according to target visual field (left, right) for each group of children.

To further control for horizontal eye movements, we rejected all segments with signals exceeding ± 50 μV at the difference waves of electrodes F9/10 during 200–400 ms before ERP averaging. To further control for eye blinking or closing during the presentation of stimulus, we also rejected all segments with signals exceeding ± 70 μV at electrodes F1/2 during 0–200 ms from the original segmented data before independent component analyses. Epochs contaminated by incorrect responses and responses faster than 200 ms or slower than 2000 ms were also excluded from the ERP averages. To assess whether any systematic horizontal electrooculography activity was present in the remaining data, we computed averaged F9/10 waveforms for left and right target trials. In all participants, residual activity was <2 μV, indicating that residual eye movements were less than ± 0.3° (31). An average of 21.3% of trials were rejected on the basis of artifacts for the final set of participants.

There were no significant differences between the number of valid trials (range, 169–190) for the ADHD and TD groups