



## Abnormalities in the anterior cingulate cortex associated with attentional and inhibitory control deficits: A neurophysiological study on children with autism spectrum disorders

Agnes S. Chan<sup>a,b,\*</sup>, Yvonne M.Y. Han<sup>a</sup>, Winnie Wing-man Leung<sup>a</sup>, Connie Leung<sup>c</sup>, Virginia C.N. Wong<sup>c</sup>, Mei-chun Cheung<sup>d</sup>

<sup>a</sup>Neuropsychology Laboratory, Department of Psychology, The Chinese University of Hong Kong, Hong Kong SAR, China

<sup>b</sup>Integrative Neuropsychological Rehabilitation Center, The Chinese University of Hong Kong, Hong Kong SAR, China

<sup>c</sup>Department of Paediatrics and Adolescent Medicine, Duchess of Kent Children's Hospital at Sandy Bay, The University of Hong Kong, Hong Kong SAR, China

<sup>d</sup>Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong SAR, China

### ARTICLE INFO

#### Article history:

Received 19 February 2010

Received in revised form 9 March 2010

Accepted 12 April 2010

#### Keywords:

Anterior cingulate  
Attention  
Inhibitory control  
EEG  
Autism  
Children

### ABSTRACT

Previous studies showed that the anterior cingulate cortex (ACC) is activated when individuals engage in attention and inhibitory control tasks. The present study examined whether ACC activity is associated with behavioral performance of the two tasks. Twenty normal and 20 children with autism spectrum disorders (ASDs) were subjected to neuropsychological assessments on attention and inhibitory control, as well as electroencephalography recording. Children with ASD performed significantly worse than normal children on attention tasks as shown in their poorer performance on the Digit Span test, the greater number of Omission Errors on both the Continuous Performance Test II and the Go/No-Go tasks. They also performed significantly worse than normal children on inhibitory control tasks as shown by the greater number of False Alarms on the Object Recognition and Hong Kong List Learning Test. Their ACC activities, as indicated by relative theta power, were found to be significantly lower than those of normal controls during performance of the Go/No-Go task. Depressed ACC activities were further found to be significantly associated with poorer performance in attention and inhibition. Clinical implications on the use of theta activities in the ACC as an indicator to monitor intervention progress in children with ASD were discussed.

© 2011 Elsevier Ltd. All rights reserved.

### 1. Introduction

Attention and inhibitory processes are important components in executive functions (Denckla, 1996; Lezak, Howieson, & Loring, 2004; Stuss, Binns, Murphy, & Alexander, 2002) that are essential for effective daily living, and are also among the most well-researched constructs in cognitive science. Attention is the ability to mindfully and consciously process stimuli (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), and includes alerting, orienting, and sustaining attention (Posner & DiGirolamo, 1998), as well as attention shifting (Courchesne et al., 1994; Hughes & Russell, 1993; Landry & Bryson, 2004). Inhibitory control refers to the suppressing of responses to irrelevant, non-target, or distracting stimuli (Enticott, Ogloff, & Bradshaw, 2006; Friedman & Miyake, 2004; Nigg, 2000). It puts a high demand on coordination including preparing for

\* Corresponding author at: Department of Psychology, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong SAR, China. Tel.: +852 2609 6654; fax: +852 2603 5019.

E-mail address: [aschan@psy.cuhk.edu.hk](mailto:aschan@psy.cuhk.edu.hk) (A.S. Chan).

responses, monitoring performance, and detecting errors (Barkley, 1997). One of the most prominent brain regions implicated in attention and inhibitory control is the anterior cingulate cortex (ACC) (Garavan, Ross, Murphy, Roche, & Stein, 2002; Menon, Adleman, White, Glover, & Reiss, 2001; Posner & Petersen, 1990; Reischies et al., 2005). A number of neuroimaging studies have found increased ACC activity during tasks that involve attention (Cabeza & Nyberg, 1997; Devinsky, Morrell, & Vogt, 1995; Elliott & Dolan, 1998); error detection (Botvinick, Cohen, & Carter, 2004; Carter et al., 2000); and response monitoring (Taylor, Stern, & Gehring, 2007). Furthermore, event-related functional magnetic resonance imaging (fMRI) studies on healthy participants have also reported altered patterns of ACC and prefrontal activation in slow responders during response inhibition tasks (Hester, Fassbender, & Garavan, 2004).

From the neurophysiological perspective, studies using electroencephalography (EEG) have widely reported that focused attention was closely associated with increased frontal midline theta power in normal individuals (Cahn & Polich, 2006; Pizzagalli, Oakes, & Davidson, 2003), and that frontal midline theta power is reflective of attentional and inhibitory processing in adults (Kropotov, Crawford, & Polyakov, 1997) and children (Chan & Leung, 2006; Daoust, Limoges, Bolduc, Mottron, & Godbout, 2004; Monastra, Lubar, & Linden, 2001; Monastra et al., 1999) patient groups. Frontal theta activity has been widely documented to be generated by the medial prefrontal cortex in the area of ACC (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999; Ishii et al., 1999; Pizzagalli et al., 2003). For example, Gevins, Smith, McEvoy, and Yu (1997), using high spatial resolution EEG combined with magnetic resonance imaging (MRI), suggested a frontal medial source for the theta in the ACC region. Similarly, Onton, Delorme, and Makeig (2005), using a dipole source model, localized the frontal midline theta to the area of dorsal ACC. In addition, electrophysiological study also revealed the source of frontal theta activity to be generated in the ACC during working memory task (Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007). Thus, we used the theta index to measure the neurophysiological activity of the ACC in the study.

While neuroimaging and neurophysiological studies have provided evidence to suggest that the ACC is involved in attention and inhibitory control, the association between ACC activities and neuropsychological performance in attention and inhibitory control has not been well studied. We thus aimed to examine whether there is an association between the two. A patient sample with autism was recruited in the present study to examine the neurophysiological dysfunction in ACC and its association with neuropsychological performance. While this patient population is considerably heterogeneous in terms of behavioral deficits as well as structural and functional neural abnormalities, it is well documented that these individuals have impairments in attention and inhibitory control (Burack, 1994; Goldstein, Johnson, & Minshew, 2001; Hazlett et al., 2004; Haznedar et al., 2000; Mundy, 2003; Nyden, Gillberg, Hjelmsquist, & Heiman, 1999; Schmitz et al., 2006), and abnormalities in the ACC (Bauman & Kemper, 1994; Gomot et al., 2006; Hazlett et al., 2004; Haznedar et al., 2006, 1997, 2000; Kana, Keller, Minshew, & Just, 2007; Luna et al., 2002; Schmitz et al., 2006; Thakkar et al., 2008).

Autism spectrum disorders (ASD) consist of a spectrum of neurodevelopmental disorders that are characterized by disturbances in communication, poor social skills, stereotyped behaviors, and deficits in memory and executive functions (Gillberg, 1993; Wing, 1997). Autism, Asperger syndrome, and pervasive developmental disorder not otherwise specified (PDD-NOS) are the three main forms of disorders in the spectrum. Autism is the core disorder of ASD, Asperger syndrome is diagnosed when the individual does not have significant delay in cognitive and language development, and PDD-NOS is diagnosed when the individual does not meet the full criteria for a more specific disorder in the spectrum (Johnson, Myers, & Council on Children with Disabilities, 2007). While the cause of ASD is not well understood, it has been suggested that in these individuals, abnormalities in their ACC are associated with executive function deficits and repetitive stereotyped behaviors (Haznedar et al., 1997; Mundy, 2003; Schmitz et al., 2006). Given the essential roles of attention (Goldstein et al., 2001) and inhibition in suppressing irrelevant thoughts and interference during executive tasks (Fernandez-Duque, Baird, & Posner, 2000), some researchers further postulated that primary deficits in attentional and inhibitory controls may account for the executive dysfunctions that underlie many of the repetitive, stereotyped behaviors in ASD (Burack, 1994; Goldstein et al., 2001; Nyden et al., 1999; Schmitz et al., 2006). Indeed, findings of numerous neuropsychological studies on ASD suggested that individuals with ASD have difficulties in response inhibitory control and slow information processing (Bishop & Norbury, 2005; Fernandez-Duque et al., 2000; Hazlett et al., 2004; Hughes, Russell, & Robbins, 1994; Nyden et al., 1999; Russell & Jarrold, 1998; Russell, Jarrold, & Hood, 1999; Schmitz et al., 2006), even though some studies failed to find such evidence (Kleinhans, Akshoomoff, & Delis, 2005; Ozonoff & Jensen, 1999; Ozonoff & Strayer, 1997). Other studies on children with ASD have also found self-monitoring impairments associated with attention and inhibitory deficits in executive functioning tasks of memory (Hill & Russell, 2002; Russell & Jarrold, 1999), error-correction (Russell & Jarrold, 1998), and in tasks that involve suppression of a prepotent response from prior learning (Bishop & Norbury, 2005; Russell et al., 1999). Neuroimaging studies, on the other hand, have shown that individuals with ASD showed atypical ACC activation when they were performing spatial working memory (Luna et al., 2002), change detection (Gomot et al., 2006), response monitoring (Thakkar et al., 2008), and response inhibition (Kana et al., 2007; Schmitz et al., 2006) tasks. In addition, reduced volume and decreased glucose metabolism in the anterior cingulate gyrus have also been found in individuals with ASD (Hazlett et al., 2004; Haznedar et al., 2006, 1997, 2000), and postmortem studies of ASD patients have demonstrated abnormalities in the cingulate cortex (Bauman & Kemper, 1994).

These studies suggested that individuals with ASD have structural, physiological, and functional abnormalities in the ACC. Based on the reported deficits in attention and inhibitory control and the documented abnormalities of the ACC in individuals with ASD, we predicted that the neurophysiological patterns associated with attentional and

inhibitory deficits in ASD should involve altered patterns of activation in the ACC. Together with findings that frontal midline theta power is reflective of attentional and inhibitory processing in children patient groups, it was postulated that the deficient attentional and inhibitory control in children with ASD would be associated with theta activity of the ACC. This hypothesis was tested by measuring theta activity in the ACC while children with ASD were performing the Go/No-Go task that involved both attention and inhibitory control. This task requires participants to focus on a computer monitor and make immediate response on “Go” trials and to inhibit their response on “No-Go” trials (Kana et al., 2007).

The purposes of this study were, therefore, to (i) examine the performance of children with ASD in attention and inhibitory control; (ii) examine the activities in their ACC when they were performing the tasks; and (iii) examine the association between the two. Since most previous studies were done on adults with ASD, children were examined in this study in the hope of extending previous knowledge to the pediatric population. It was hypothesized that children with ASD would perform significantly poorer than normal children in attention and inhibition; that under the task condition, children with ASD would show different ACC theta activities compared with normal children; and that attention and inhibition performance would be associated with ACC theta activities.

## 2. Material and methods

### 2.1. Participants

Twenty normal children and 20 children with ASD (17 with autistic disorder, two with Asperger disorder, one with pervasive developmental disorder not otherwise specified), aged 7–14 years, participated voluntarily in the study. Normal control (NC) children were recruited from local primary schools or from the database of our laboratory. Invitation letters were sent to parents through the schools, and all children whose parents indicated an interest to participate were recruited. All NC children had negative history of neurological problems or abnormal developmental milestones as reported by the parents. Children with ASD were recruited from the Parents' Association of Pre-School Handicapped Children in Hong Kong or from the subject database of our laboratory. They were previously diagnosed, based on the criteria in the *Diagnostic and Statistical Manual of Mental Disorders* (4th edition) (DSM-IV; American Psychiatric Association, 2002) or the Autism Diagnostic Observation Schedule (ADOS) (Lord, Rutter, DiLavore, & Risi, 2002), by pediatricians of Child Assessment Centres in Hong Kong. Diagnosis was further confirmed by a clinical psychologist through standard clinical interview and the Childhood Autism Rating Scale (Schopler, Reichler, & Renner, 1998). Table 1 shows the demographic characteristics of the children. Both the ASD and NC groups were matched on age,  $t(38) = 1.51, p > .05$ , general intelligence as measured by the Test of Non-verbal Intelligence, 3rd edition (TONI-III) (Brown, Sherbenou, & Johnsen, 1992;  $t(38) = -1.7, p > .05$ ), and had equal gender distribution. It should be noted that the male to female ratio of 19:1 was considerably higher than the reported mean ratio of 4.3:1 (Fombonne, 2003). As many of the assessment measures used in this study are dependent on motor skills, all children recruited were without physical disabilities or reported motor dysfunction.

### 2.2. Procedures and materials

All children were individually administered a neuropsychological battery that included the TONI-III (Brown et al., 1992) and neuropsychological measures of attention and inhibition including the Continuous Performance Test II (Conners, 2000), Digit Span (forward) test (Hong Kong Education Department & Hong Kong Psychological Society, 1981), Hong Kong List Learning Test (Chan, 2006), and Object Recognition Test (Rossion & Pourtois, 2004). The children were also subjected to an EEG recording session where EEG was recorded for a 6-min period while they performed the Go/No-Go task. Because of the short attention span and aversion to novel tactile stimulation of this particular patient group, a short recording time was necessary to ensure that the children could complete the Go/No-Go task, especially with the EEG cap connected to their heads. The sequence of the neuropsychological assessment and EEG recording was counter-balanced to avoid order effect. The experimental and EEG recording procedures were explained to the children and parents before the experiment started, and all children participated with informed parental consent. The procedure was approved by the Joint CUHK-NTEC Clinical Research Ethics Committee.

**Table 1**  
Demographic characteristics of the normal controls (NC) and children with autistic spectrum disorders (ASD).

Variable	NC ( $n = 20$ )	ASD ( $n = 20$ )
Mean age (in years)	9.8 (1.88)	10.75 (2.07)
Gender (male/female)	19/1	19/1
TONI-III (deviation quotient)	110.7 (17.84)	101.4 (16.83)
CARS (total score)	–	31.98 (3.31)

Note: Standard deviations are in parentheses. CARS=Childhood Autism Rating Scale; TONI-III=Test of Non-verbal Intelligence, 3rd edition. The dash indicates that the CARS was not administered to normal controls.

## 2.3. Measures

### 2.3.1. Test of Non-verbal Intelligence

The TONI-III (Brown et al., 1992) was administered to assess non-verbal intelligence. This test consists of 45 matrix reasoning questions, giving a raw score that ranged from 0 to 45, which is then converted to a deviation quotient based on the norms provided in the test manual.

### 2.3.2. Digit Span (DS) forward

This test is a subtest on the Hong Kong version of the Wechsler Intelligence Scale for Children (Hong Kong Education Department & Hong Kong Psychological Society, 1981) on short-term memory and attention, and was used to assess attention in the present study. It consists of a list of nine random numerals read aloud in sequence by the examiner at the rate of one numeral per second, starting from two numerals up to nine numerals in a total of eight trials. Participants are asked to repeat the numerals after the examiner, in sequence, after each trial. The score is the number of correct trials recalled by the participant.

### 2.3.3. Hong Kong List Learning Test (HKLLT)

The HKLLT (Chan, 2006) was used in the study to measure frontal lobe functions including learning strategies, organization, and vulnerability to interference. This is an oral test consisting of a randomly organized list of 16 two-word Chinese characters presented once during each of the three learning trials. A recognition test consisting of the 16 target words and 16 distracters was presented after the 30-min delayed recall trial. The number of False Alarms was recorded as intrusion errors, which is commonly a neuropsychological measure of inhibition (Chan, Cheung, Han, et al., 2009; Cunningham, Pliskin, Cassisi, Tsang, & Rao, 1997; De Beni & Palladino, 2004; Mahone, Koth, Cutting, Singer, & Denckla, 2001; Stuss et al., 1994).

### 2.3.4. Object Recognition (OR) Test

This test was used to measure non-verbal memory in the study. It consisted of 24 line drawings taken from Snodgrass and Vanderwart (1980) object database, modified and validated by Rossion and Pourtois (2004). The line drawings were placed in a six by four array displayed on a computer screen for 3 min. Participants were required to memorize the items for a later recognition task that consisted of 12 targets mixed with 12 distractors. Incorrect identification of distractors was counted as False Alarms, which is a common measure of intrusion and inhibition (Cornoldi & Mammarella, 2006). Scores on this test ranged from 0 to 12.

### 2.3.5. Continuous Performance Test II

The CPT-II (Conners, 2000) was administered on the computer and measured sustained attention, impulse control, and information processing speed. Participants were required to press a key as quickly as possible in response to letters of the alphabet displayed on the computer screen, with the exception of the letter "X". Total Omission Errors measured attention; Total Commission Errors measured inhibitory control; and information processing efficiency was reflected in the Hit Reaction Time.

### 2.3.6. Go/No-Go task

The computerized Go/No-Go task was used to measure sustained attention, impulse control, and information processing speed in the study. Children were required to press a key as quickly as possible when a black ball (Go stimulus) appeared on the computer screen, and to inhibit their responses when a red ball (No-Go stimulus) appeared. The total testing time was 6 min and the stimuli were displayed one at a time, in the center of the computer screen, for 500 ms in random order at a ratio of 4:1 (192 black balls:48 red balls) followed by 1000 ms of blank intervals. The Total Omission Errors on "Go" trials measured attention, the Total Commission Errors on "No-Go" trials measured inhibition, and Hit Reaction Time measured information processing efficiency.

### 2.3.7. EEG recording

All parents and children were briefed on the procedure, and informed consents were obtained before EEG recordings were taken. EEG data were collected during the Go/No-Go task using an electrode cap with 19 electrode sites (International 10–20 System) referenced to linked ears. The EEG signal was digitized at 256 Hz with a low pass filter of 30 Hz and impedances below 10 k $\Omega$ . EEG data were stored and later displayed on computer, and visually examined for eye movements and muscle artifacts. Only data that had at least 1 min of artifact-free data were selected (see John, Pritchep, Fridman, & Easton, 1988 for discussion of qEEG method) and spectrally processed using the fast Fourier Transformation (FFT) to compute power data for the theta band (4–7.5 Hz).

### 2.3.8. EEG data reduction

EEG data for each participant was first transformed by Excel application before they were imported into the software EEGLAB using MatLab 7.1 to capture correct events and epochs. The average reaction time for normal individuals was set at around 300–400 ms (Miller & Low, 2001). This was calculated based on the assumption that normal individuals take around

90 ms to perceive the appearance of a visual object, followed by cognitive appraisal, which in turn leads to motor action. To ensure that the selected epoch would adequately bracket the data corresponding to the inhibition task, the epoch limit was set as 50 ms as the start and 900 ms as the end. Artifacts in epoched data were then pruned by visual inspection and using the rejection method on EEG Plot. All incorrect hits were also deselected. The transformed data were exported into readable format for analysis using the NeuroGuide software.

### 2.3.9. Relative theta

EEG data recorded from the 19 electrode sites were averaged to obtain grand means for the anterior (F3, F4, F7, F8, Fz), centrottemporal (C3, C4, T3, T4, T5, T6, Cz), and posterior (P3, P4, O1, O2, Pz) regions for further analysis. Relative power was used for analyses on the theta band based on the rationale that (1) relative power measurements tend to give larger estimates for the dominant frequency range (Klimesch, 1999), and (2) individual variations are eliminated by computing the proportion of an individual frequency band relative to the others (Chan, Sze, & Cheung, 2007).

### 2.3.10. Source analysis

Previous findings implicated the ACC as a generator for frontal midline theta activities in the human brain (Asada et al., 1999; Ishii et al., 1999; Pizzagalli et al., 2001). To localize the sources of the theta activities in response to the “Go” and “No-Go” conditions, we employed low-resolution electromagnetic tomography (LORETA) (Pascual-Marqui et al., 1999; Pascual-Marqui, Michel, & Lehmann, 1994). The sources of the theta activities were expressed as three-dimensional cortical current density according to the Talairach brain atlas. All EEG data used for FFT were analyzed with LORETA during the two experimental (Go, No-Go) conditions.

## 2.4. Data analyses

ASD and NC children were compared on their performance on the neuropsychological measures on attention and inhibitory control, which included 9 scores from the DS, HKLLT, OR, CPT-II, and Go/No-Go tasks using independent *t*-tests. To examine the neurophysiological changes in relative theta power in response to the “Go” and “No-Go” conditions, a  $2 \times 2 \times 3$  (Diagnosis  $\times$  Condition  $\times$  Region) analysis of variance (ANOVA) with repeated measures was performed, with Condition (Go, No-Go), and Region (anterior, centrottemporal, posterior) as within-subject factors, and Diagnosis (NC, ASD) as between-subject factor. This was followed by post hoc *F*-tests to pinpoint the brain regions showing significant differences in the theta band. Relationships between attention, inhibition and EEG activities across the ASD and NC groups were examined using Pearson correlation. To examine whether the correlations reflect only basic group differences, subgroup analyses (NC = 20, ASD = 20) were done. Given that specific hypotheses were tested and that the number of participants were relatively small, we did not adjust the alpha level to avoid lowering the power of the tests.

## 3. Results

### 3.1. Neuropsychological measures

The ASD group showed significantly poorer performance on the DS ( $t = -2.98, p < .01$ ) than the normal group, as well as significantly higher False Alarms on the OR ( $t = 4.04, p < .01$ ) and the HKLLT ( $t = 2.76, p < .01$ ). For the Go/No-Go task, the ASD and NC groups did not differ significantly in the number of Total Commission Errors ( $t = 1.91, n.s.$ ) during the “No-Go” trials.

**Table 2**  
Mean performance and standard deviation on the attention and inhibitory control of children in the NC and ASD groups.

Measures	NC ( $n = 20$ ) <i>M</i> (SD)	ASD ( $n = 20$ ) <i>M</i> (SD)	<i>t</i> -Value
DS			
Forward	12.79 (1.85)	10.17 (2.62)	-2.98**
HKLLT			
False Alarms	.35 (.59)	4.05 (5.82)	2.76**
OR			
False Alarms	.05 (.22)	3.05 (3.32)	4.04**
Go/No-Go			
Hit Reaction Time (ms)	374.7 (61.8)	425.2 (145)	1.43
Omission Errors	4.6 (4.58)	16.5 (18.92)	2.73**
Commission Errors	8.9 (5.56)	12.8(7.23)	1.91
CPT			
Hit Reaction Time (ms)	412.42 (66.3)	479.44 (130.6)	1.92
Omission Errors	3.8 (1.33)	17.76 (23.07)	-2.46*
Commission Errors	23.15 (5.66)	23.18 (5.41)	.01

The mean performance of CPT task was computed based on 20 NC and 17 ASD children.

\*  $p < .05$ .  
\*\*  $p < .01$ .

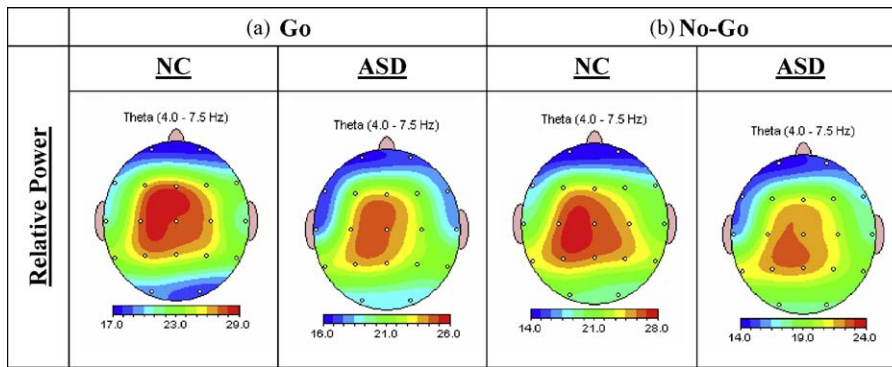


Fig. 1. Topographic maps demonstrating the mean values of relative theta power, with the frontal regions at the top of each map, are shown for normal children (NC), and children with autistic spectrum disorder (ASD) during (a) Go and (b) No-Go conditions.

Independent  $t$ -test also showed no significant difference between the two groups on Hit Reaction Time ( $t = 1.44, n.s.$ ) on the Go/No-Go task. The ASD group, however, produced significantly more Total Omission Errors ( $t = 2.73, p < .01$ ) than the NC group during the “Go” trials. For the CPT-II, three outliers in the ASD group were excluded in the analysis because of the unreasonably large amount of Omission Errors ( $>3SD$ ) suggesting that they were not performing the test according to the instructions. Results on the CPT-II were consistent with those on the Go/No-Go task, in that no significant difference was found between the ASD and NC groups on Hit Reaction Time ( $t = 1.92, p > .05$ ) and Total Commission Errors ( $t = .01, p > .05$ ). The ASD group, however, showed significantly higher Total Omission Errors ( $t = 2.46, p < .05$ ) than the normal group (Table 2). While the children with ASD showed significantly poorer performance in various attention and inhibition tasks

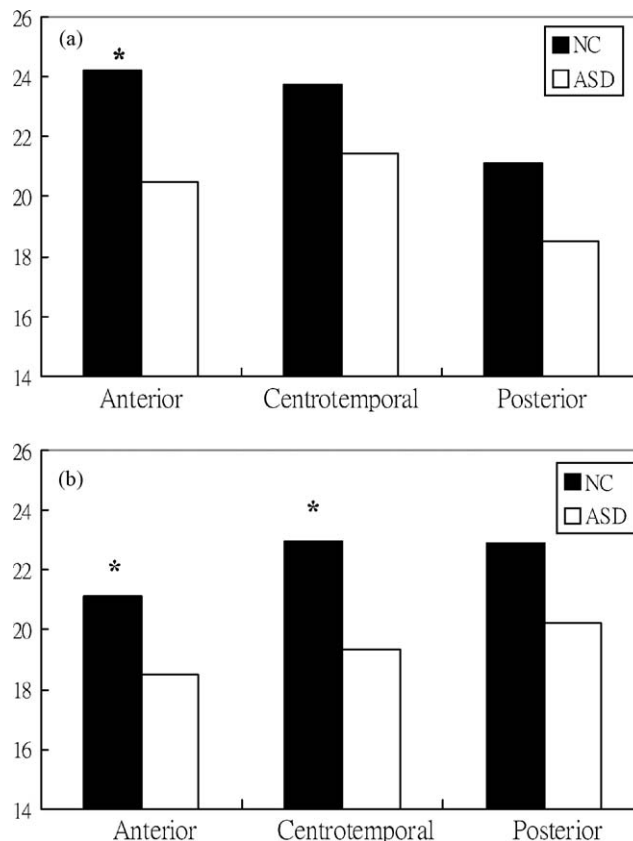


Fig. 2. (a) Go condition: Children with autistic spectrum disorder (ASD) showed significantly lower mean relative theta values (%) than normal control (NC) in the anterior region, but not in the centrottemporal and posterior regions. (b) No-Go condition: Children with ASD demonstrated significantly lower mean relative theta values in the anterior and centrottemporal regions, but not in the posterior region.  $p < .05$ .

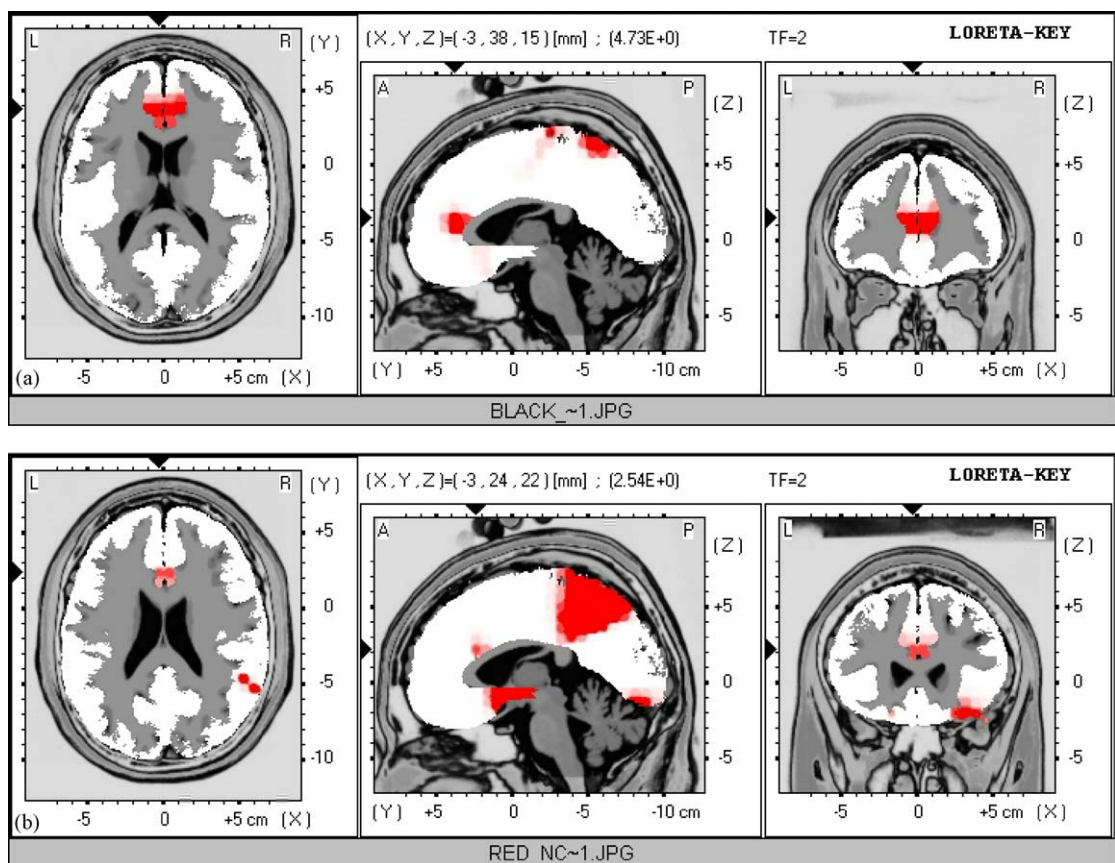
than normal controls, it should be noted the ASD group also showed large within-group variability, violating the assumption of homogeneity of variances. The set of *t*-test results with homogeneity not assumed was thus used.

### 3.2. Neurophysiological measures

Maps showing the regional relative theta power of the ASD and NC groups are presented in Fig. 1. Visual examination showed that relative theta power was lower across multiple channels in the ASD group. Repeated measures ANOVA results showed no significant interaction effect of *Diagnosis* × *Condition* [ $F(1,38)=1.38, p > .05$ ] and of *Diagnosis* × *Region* [ $F(2,76)=2.03, p > .05$ ]. The results, however, indicated a significant *Condition* × *Region* interaction for the theta band [ $F(2,76)=5.28, p < .05$ ], and a significant between-subject effect [ $F(1,38)=6.91, p < .05$ ]. For the “Go” condition, tests of simple effects demonstrated that the ASD group showed significant decrease in relative theta power than normal children in the anterior [ $F(1,38)=14.41, p < .05$ ] but not the centrottemporal [ $F(1,38)=4.03, p > .05$ ] and posterior [ $F(1,38)=.56, p > .05$ ] brain regions. For the “No-Go” condition, the ASD group showed significant decrease in relative theta power in the anterior [ $F(1,38)=5.88, p < .05$ ] and the centrottemporal [ $F(1,38)=8.61, p < .05$ ] but not the posterior [ $F(1,38)=3.08, p > .05$ ] region as compared to the normal control group (Fig. 2).

### 3.3. Localization of theta activity

To examine whether the ASD group differed from the normal group in the sources of the theta activity, source analysis was conducted using the LORETA voxel-by-voxel *t*-value to compare theta activities of the ASD and NC groups on the “Go” and “No-Go” conditions. Compared with the normal controls, results revealed that the ASD group showed significantly reduced theta activities in the ACC during the “Go” [Brodmann area 24;  $t=4.83 (p < .05)$ ] and “No-Go” [Brodmann area 24,  $t=2.61 (p < .05)$ ] conditions. In addition to the reduced activation in ACC for the “No-Go” condition, a more significant underactivation was also found in the Precuneus [Brodmann area 7,  $t=3.01 (p < .05)$ ] (Fig. 3).



**Fig. 3.** Graphical representation of the LORETA *t*-statistics comparing the (a) Go-related and (b) No-Go-related activations of the ASD and NC groups. Red color indicates the location of significantly reduced electrical activity in the brain of the ASD group as compared to the normal controls. The location of voxel is defined by the Talairach coordinates (X, Y, Z) and the black arrows indicate the center of difference in ACC activity (Brodmann area 24). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

**Table 3**Correlations between anterior relative theta power, IQ, and mean performance on neuropsychological tests ( $n=40$ ).

	Go Anterior theta	No-Go Anterior theta	TONI-III	Go/No-Go Omission Errors	CPT Omission Errors	DS Forward	OR False Alarms	HKLLT False Alarms
Go–Anterior theta	1.00							
No-Go–Anterior theta	.72***	1.00						
TONI-III	-.21	-.13	1.00					
Go/No-Go–Omission Errors	-.10	-.22	-.37*	1.00				
CPT–Omission Errors	-.09	-.21	-.34*	.75***	1.00			
DS–Forward	.40*	.26	.40*	.54**	-.56**	1.00		
OR–False Alarms	-.42**	-.50***	-.35*	.58***	.61***	-.61***	1.00	
HKLLT–False Alarms	-.32*	-.08	-.34*	.66***	.84***	-.71***	.60***	1.00

\*  $p < .05$ .\*\*  $p < .01$ .\*\*\*  $p < .001$ .**Table 4**

Correlations between anterior relative theta power, IQ, and mean performance on neuropsychological tests for the ASD and NC subgroups.

	Go Anterior theta	No-Go Anterior theta	TONI-III	Go/No-Go Omission Errors	CPT Omission Errors	DS Forward	OR False Alarms	HKLLT False Alarms
ASD ( $n=20$ )								
Go–Anterior theta	1.00							
No-Go–Anterior theta	.70***	1.00						
TONI-III	-.22	-.08	1.00					
Go/No-Go–Omission Errors	-.01	-.05	-.43	1.00				
CPT–Omission Errors	-.26	.01	-.36	.73*	1.00			
DS–Forward	.59*	.10	.27	-.55	-.62	1.00		
OR–False Alarms	-.26	-.47*	-.36	.49*	.39	-.57	1.00	
HKLLT–False Alarms	-.19	.09	-.40	.63**	.87***	-.77**	.48*	1.00
NC ( $n=20$ )								
Go–Anterior theta	1.00							
No-Go–Anterior theta	.61**	1.00						
TONI-III	-.40	-.26	1.00					
Go/No-Go–Omission Errors	-.09	-.27	-.04	1.00				
CPT–Omission Errors	-.19	-.34	-.14	.32	1.00			
DS–Forward	.42	.04	.44	.24	-.49	1.00		
OR–False Alarms	-.24	-.11	-.10	-.13	.04	-.19	1.00	
HKLLT–False Alarms	-.16	-.01	-.02	-.02	.18	-.26	.14	1.00

\*  $p < .05$ .\*\*  $p < .01$ .\*\*\*  $p < .001$ .

### 3.4. Association between attention, inhibition and theta activities in the ACC

Given that children with ASD were found to differ from normal children in their task-related ACC theta activities as indicated by the anterior relative theta power, and in measures of attention and inhibitory control as indicated by performance on the neuropsychological assessments, we examined the association between the two using Pearson correlations on the whole group of children and separately for the ASD and normal subgroups. Anterior theta power during the “Go” condition for the combined group was significantly correlated with DS ( $r = .40$ ,  $p < .05$ ), OR False Alarms ( $r = -.42$ ,  $p < .01$ ), and HKLLT False Alarms ( $r = -.32$ ,  $p < .05$ ); and anterior theta power during the “No-Go” condition was significantly correlated with OR False Alarms ( $r = -.50$ ,  $p < .001$ ) (Table 3). In the subgroup analysis, findings on the ASD group were consistent in that anterior theta power during the “Go” condition was significantly correlated with DS ( $r = .59$ ,  $p < .05$ ), and anterior theta power during the “No-Go” condition was significantly correlated with OR False Alarms ( $r = -.47$ ,  $p < .05$ ). Although no significant association between OR False Alarms ( $r = -.26$ ,  $p > .05$ ) and HKLLT False Alarms ( $r = -.19$ ,  $p > .05$ ) with anterior relative theta power was found as in the combined-group analysis, this was likely to be due to the lower power as a result of the smaller number of participants in the subgroup analysis. No significant association of the neurophysiological and neuropsychological responses was found in the NC group (Table 4).

## 4. Discussion and conclusions

This study investigated whether neuropsychological deficits in attention and inhibitory control were associated with their neurophysiological activity on a group of children with ASD during their performance of such tasks. Results on the

neuropsychological performance confirmed the hypothesis that children with ASD performed poorer than normal children on measures of attention including significantly poorer performance on the DS test, and committed significantly more Omission Errors on CPT-II and the “Go” trial of the Go/No-Go tasks. They also performed significantly poorer on measures of inhibition including committing significantly more False Alarms on the HKLLT and the OR. Findings on the neurophysiological activities also confirmed the hypothesis that under the task condition, children with ASD would show different ACC theta activities. Children with ASD in the present study exhibited lower relative theta activities in the anterior brain region and less activation in the ACC, localized by LORETA estimation, in both “Go” and “No-Go” conditions compared with normal controls. The hypothesis that attention and inhibition performance would be associated with ACC theta activities was also confirmed. Examination across the NC and ASD groups showed that depressed theta activities in the ACC during the “Go” condition (i.e. attention) was significantly associated with poorer performance in attention measures including the DS, HKLLT False Alarm and OR False Alarm. Depressed theta activities in the ACC during the “No-Go” condition (i.e. inhibition) were also found to be significantly associated with poorer performance in the inhibition measure of OR False Alarm. Subgroup analysis showed that a similar pattern was also observed in children with ASD.

The present findings are in line with previous findings that individuals with ASD had deficits in attentional (Goldstein et al., 2001; Nyden et al., 1999; Sturm, Fernell, & Gillberg, 2004) and inhibitory controls (Bishop & Norbury, 2005; Chan, Cheung, Han, et al., 2009; Chan, Cheung, Sze, Leung, & Shi, 2009; Chan, Cheung, Tsui, Sze, & Shi, 2009; Fernandez-Duque et al., 2000; Hazlett et al., 2004; Hughes et al., 1994; Russell & Jarrold, 1998; Russell et al., 1999). In the present study, children with ASD performed comparably with normal children in Commission Errors but poorly in Omission Errors on both the Go/No-Go and CPT-II tasks, suggesting that they were within the normal range in simple inhibitory control but showed impairments in attention. These findings are in line with prior studies that reported attention deficits in children with ASD (Bishop & Norbury, 2005; Nyden et al., 1999), resulting in increased rate of Omission Errors. The results are also consistent with previous findings that inhibition deficit in ASD were not pervasive but depended on the complexity of the task (Kana et al., 2007). As suggested by some researchers, response inhibition does not occur in isolation, but is a key executive process that governs the coordination of other facets of processing so that a response is inhibited at just the right time (Denckla, 2002; Kana et al., 2007; Nyden et al., 1999). This may explain why children with ASD in the present study were relatively unimpaired in the simple Go/No-Go and CPT-II tasks, but showed impaired performance in intrusion and False Alarms on the more complex HKLLT and OR tasks which required multiple executive functions (Stuss et al., 1994).

Findings in the present study on the association between ACC dysfunction and cognitive impairments were also consistent with reported findings for adults with ASD (Haznedar et al., 2000; Henderson et al., 2006; Mundy, 2003; Shafritz, Dichter, Baranek, & Belger, 2008). Children with ASD in the present study demonstrated significantly lower frontal midline relative theta power, indicating reduced activation of the ACC, when performing the attention- and inhibition-demanding Go/No-Go task. The ACC has been found to play a central role in several complex functions associated with attention (Kok, Ridderinkhof, & Ullsperger, 2006; Schmitz et al., 2006) and response inhibition, such as the monitoring of task performance (Botvinick et al., 2004; Bush, Luu, & Posner, 2000). These relatively complex information processing tasks are those that individuals with ASD have difficulty with (Minshew, Meyer, & Goldstein, 2002). In addition to the reduced signal estimated from the ACC, children with ASD in our study also showed significantly depressed relative theta power in the parietal region during the response inhibition task of the “No-Go” trials compared with normal children. These results are consistent with previous findings that suggested significant parietal involvement in response inhibition (Kana et al., 2007; Liddle, Kiehl, & Smith, 2001; Menon et al., 2001). Specifically, the parietal region, in conjunction with the ACC, has been shown to play a fundamental role in error detection (Carter et al., 1998), response conflict (Braver, Barch, Gray, Molfese, & Snyder, 2001; Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001), and visual-spatial alerting and orienting (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Coull, Frith, Frackowiak, & Grasby, 1996). Hence, the depressed relative theta power over the parietal and ACC regions during the response inhibition task of the “No-Go” trials suggests problem with inhibitory control in children with ASD in our study.

It is worth noting that the depressed theta power found in children with ASD in the present study is in contrast with prior studies on adults which showed greater theta power (Daoust et al., 2004; Murias, Webb, Greenson, & Dawson, 2007). It has been well documented that resting theta power decreases with age (Gasser, Jennen-Steinmetz, Sroka, Verleger, & Mocks, 1988; Gasser, Verleger, Bacher, & Sroka, 1988; Harmony et al., 1990; Somsen, Van-Klooster, Van-der-Molen, & Van-Leeuwen, 1997), and the mature brain is characterized by a reduction in theta power as compared to the less developed brain in younger children (Klimesch, 1999; Schmid, Tirsch, & Reitmeir, 1997) and in individuals with educational problems (Gasser, Rousson, & Gasser, 2003; Harmony et al., 1995), learning disabilities (Byring, Salmi, Sainio, & Orn, 1991; Harmony et al., 1995; Pinkerton, Watson, & McClelland, 1989) and neurological disorders (Ahn et al., 1980; Coben, Clarke, Hudspeth, & Barry, 2008; John et al., 1983). The higher theta power in adults with ASD is akin to the less developed brains of younger children, suggesting a lag in brain development which may be associated with their pervasive cognitive impairments. Along this line of thinking, one would expect that children with ASD would also show elevated theta power compared to normal children. The findings of depressed theta power in this study seem to suggest that such maturation lag is not yet evident in pre-adolescence children with ASD. However, it should also be noted that in children, theta power may not yet be functionally differentiated from other frequency ranges, in particular the alpha (Klimesch, 1999), and thus the decrease in theta rhythm observed in the ASD group might actually be due to a decrease in other normal rhythms identified in children.

What appears to be an important extension of previous studies is that in the present study, it was found that depressed neurophysiological activities in the ACC were significantly associated with poorer performance in attention and inhibition.

This provided some empirical evidence to support the notion that functional abnormality in the ACC may underlie the deficits in attentional and inhibitory control in children with ASD. This relationship, in addition to increasing the knowledge of the neurophysiological basis of behavioral dysfunction associated with ASD, may also have clinical implications for intervention for children with ASD. As theta activities in the ACC are found to be associated with inhibitory deficits in children with ASD, this EEG marker may be used as a quick and objective indicator to monitor the progress of children with ASD undergoing intervention programs. With this quick and objective method, clinicians would have an alternative than to put these children through lengthy neuropsychological assessments commonly available in most clinics, which may be difficult for this patient group. This is especially useful for non-verbal children with ASD, as verbal neuropsychological tests are not applicable to this patient group. However, the fact that clinics may not have ready access to EEG equipment may pose a limitation on the more widespread use of this method. Another advantage of using this EEG marker over the use of conventional neuropsychological tests is that it is less time intensive, on one hand making it more acceptable for children with ASD, and on the other reducing the time involvement of professional psychologists which in turn may reduce the cost of intervention for patients. Apart from using this EEG marker in treatment monitoring, the possibility of developing interventions to improve ACC functioning may also be another research direction on children with ASD (Chan, Cheung, Sze, et al., 2009; Chan, Cheung, Tsui, et al., 2009).

While there are some interesting observations in the present study that suggested an association between attention, inhibitory control and neurophysiological activities, the following should be noted when interpreting the data. First, it should be noted that since the ADOS and ADI-R are not routinely used for diagnosis of ASD in Hong Kong due to the lack of locally validated versions, not all children with ASD in the present study were diagnosed using this gold standard. Second, the measures used, i.e. intrusion errors, were relatively simple and indirect measures of inhibitory control (De Beni & Palladino, 2004). In addition, the theta power associated with the “Go” and “No-Go” conditions was highly correlated in the present study, which may suggest possible involvement of a common underlying function rather than differences in inhibition and attention. Further research with other inhibitory control measures is necessary before we can establish for certain the relationship between intrusion error, inhibitory control, and ACC activities. Third, the use of the non-verbal TONI-III as a surrogate measure for general intelligence has some limitations: the absence of a measure of verbal intelligence may introduce a potential confound for task performance especially in the word learning test; and the use of only non-verbal IQ to represent general intelligence may make the participants appear more similar than they actually are. Fourth, while all children did not have physical disabilities or motor dysfunctions, the lack of control on the children’s motor abilities should be noted as many of the assessments involved motor skills. Finally, caution is raised towards the generalization of the findings due to the relatively small sample-size; the non-random selection of the children; and for children with ASD the large within-group variations in performance, the overrepresentation of high-functioning children, the young age-group, and the high ratio of boys to girls making it difficult to draw conclusions on girls. When interpreting the data, these limitations should be borne in mind. Given the potentially useful clinical application of the neurophysiological measure of frontal midline theta power, further studies are warranted to examine the use of this measure on individuals with ASD from a larger age range and at different levels of functioning.

## Acknowledgments

This research was supported by the research grant CUHK 440407 from the Hong Kong Research Grants Council. We thank the Parents’ Association of Pre-School Handicapped Children in Hong Kong for their assistance in recruiting participants.

## References

- Ahn, H., Pritchep, L., John, E. R., Baird, H., Trepetin, M., & Kaye, H. (1980). Developmental equations reflect brain dysfunctions. *Science*, *210*, 1259–1262.
- American Psychiatric Association. (2002). *Diagnostic and statistical manual of mental disorders* (4th ed., text revision). Washington, DC: Author.
- Asada, H., Fukuda, Y., Tsunoda, S., Yamaguchi, M., & Tonoike, M. (1999). Frontal midline theta rhythms reflect alternative activation of prefrontal cortex and anterior cingulate cortex in humans. *Neuroscience Letters*, *274*, 29–32.
- Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65–94.
- Bauman, M. L., & Kemper, T. L. (1994). Neuroanatomic observations of the brain in autism. In M. L. Bauman & T. L. Kemper (Eds.), *The neurobiology of autism* (pp. 119–145). Baltimore: Johns Hopkins Press.
- Bishop, D. V. M., & Norbury, C. F. (2005). Executive functions in children with communication impairments, in relation to autistic symptomatology. 2: Response inhibition. *Autism*, *9*, 29–43.
- Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Science*, *8*, 539–546.
- Braver, T. S., Barch, D. M., Gray, J. R., Molfese, D. L., & Snyder, A. (2001). Anterior cingulate cortex and response conflict: Effects of frequency, inhibition and errors. *Cerebral Cortex*, *11*, 825–836.
- Brown, L., Sherbenou, R. J., & Johnsen, S. K. (1992). *Test of nonverbal intelligence: A language-free measure of cognitive ability* (3rd ed.). Austin, TX: PRO-ED.
- Burack, J. A. (1994). Selective attention deficits in persons with autism: Preliminary evidence of an inefficient lens. *Journal of Abnormal Psychology*, *103*, 535–543.
- Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in the anterior cingulate cortex. *Trends in Cognitive Science*, *4*, 215–222.
- Byring, R. F., Salmi, T. K., Sainio, K. O., & Orn, H. P. (1991). EEG in children with spelling disabilities. *Electroencephalography and Clinical Neurophysiology*, *79*, 247–255.
- Cabeza, R., & Nyberg, L. (1997). Imaging cognition: An empirical review of PET studies with normal subjects. *Journal of Cognitive Neuroscience*, *9*, 1–26.
- Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin*, *132*, 180–211.
- Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection and the online monitoring of performance. *Science*, *280*, 747–749.

- Carter, C. S., Macdonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., et al. (2000). Parsing executive processes: Strategic vs evaluative functions of the anterior cingulate cortex. *PNAS*, 97(4), 1944–1948.
- Chan, A. S. (2006). *Hong Kong List Learning test* (2nd ed.). Hong Kong: Department of Psychology and Clinical Psychology Centre, The Chinese University of Hong Kong.
- Chan, A. S., Cheung, M. C., Han, Y. M. Y., Sze, S. L., Leung, W. W., Man, H. S., et al. (2009). Executive function deficits and neural discordance in children with autism spectrum disorders. *Clinical Neurophysiology*, 120, 1107–1115.
- Chan, A. S., Cheung, M. C., Sze, S. L., Leung, W. W., & Shi, D. (2009). An herbal nasal drop enhanced frontal and anterior cingulate cortex activity. *Evidence-based Complementary and Alternative Medicine*. Advance Access published online December 8, 2009, eCAM, doi:10.1093/ecam/nep198.
- Chan, A. S., Cheung, M. C., Tsui, W. J., Sze, S. L., & Shi, D. (2009). Dejian Mind–Body Intervention on depressive mood of community-dwelling adults: A randomized controlled trial. *Evidence-based Complementary and Alternative Medicine*. Advance Access published online May 27, 2009, eCAM, doi:10.1093/ecam/nep043.
- Chan, A. S., & Leung, W. W. M. (2006). Differentiating autistic children with quantitative encephalography: A 3-month longitudinal study. *Journal of Child Neurology*, 21, 391–399.
- Chan, A. S., Sze, S. L., & Cheung, M. (2007). Quantitative electroencephalographic profiles for children with autistic spectrum disorder. *Neuropsychology*, 21(1), 74–81.
- Coben, R., Clarke, A. R., Hudspeth, W., & Barry, R. J. (2008). EEG power and coherence in autism spectrum disorder. *Clinical Neurophysiology*, 119, 1002–1009.
- Conners, C. K. (2000). *Conner's Continuous Performance Test II*. ON: Multi-Health System.
- Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, 3, 292–297.
- Cornoldi, C., & Mammarella, N. (2006). Intrusion errors in visuospatial working memory performance. *Memory*, 14, 176–188.
- Coull, J. T., Frith, C. D., Frackowiak, R. S., & Grasby, P. M. (1996). A frontal-parietal network for rapid visual information processing: A PET study of sustained attention and working memory. *Neuropsychologia*, 34, 1085–1095.
- Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., et al. (1994). Impairment in shifting attention in autistic and cerebellar patients. *Behavioral Neuroscience*, 108, 848–865.
- Cummingham, J. M., Pliskin, N. H., Cassisi, J. E., Tsang, B., & Rao, S. M. (1997). Relationship between confabulation and measures of memory and executive function. *Journal of Clinical and Experimental Neuropsychology*, 19, 867–877.
- Daoust, A.-M., Limoges, E., Bolduc, C., Mottron, L., & Godbout, R. (2004). EEG spectral analysis of wakefulness and REM sleep in high functioning autistic spectrum disorders. *Clinical Neurophysiology*, 115, 1368–1373.
- De Beni, R., & Palladino, P. (2004). Decline in working memory updating through ageing: Intrusion error analyses. *Memory*, 12, 75–89.
- Denckla, M. B. (1996). Biological correlates of learning and attention: What is relevant to learning disability and attention-deficit hyperactivity disorder? *Journal of Developmental and Behavioral Pediatrics*, 17, 114–119.
- Denckla, M. B. (2002). The behavior rating inventory of executive function: Commentary. *Child Neuropsychology*, 8, 304–306.
- Devinsky, O., Morrell, M. J., & Vogt, B. A. (1995). Contributions of anterior cingulate cortex to behaviour. *Brain*, 118, 279–306.
- Elliott, R., & Dolan, R. J. (1998). Activation of different anterior cingulate foci in association with hypothesis testing and response selection. *Neuroimage*, 8, 17–29.
- Enticott, P. G., Oglhoff, J. R. P., & Bradshaw, J. L. (2006). Associations between laboratory measures of executive inhibitory control and self-reported impulsivity. *Personality and Individual Differences*, 4, 285–294.
- Fernandez-Duque, D., Baird, J. A., & Posner, M. I. (2000). Executive attention and metacognitive regulation. *Consciousness and Cognition*, 9, 288–307.
- Fombonne, E. (2003). Epidemiological surveys of autism and other pervasive developmental disorders: An update. *Journal of Autism Developmental Disorders*, 33, 365–382.
- Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General*, 133, 101–135.
- Garavan, H., Ross, T. J., Murphy, K., Roche, R. A. P., & Stein, E. A. (2002). Dissociable executive functions in the dynamic control of behavior: Inhibition, error detection, and correction. *Neuroimage*, 17(4), 1820–1829.
- Gasser, T., Jennen-Steinmetz, C., Sroka, L., Verleger, R., & Mocks, J. (1988). Development of the EEG for school-age children and adolescents: II. Topography. *Electroencephalography and Clinical Neurophysiology*, 69, 100–109.
- Gasser, T., Rousson, V., & Gasser, U. S. (2003). EEG power and coherence in children with educational problems. *Journal of Clinical Neurophysiology*, 20, 273–282.
- Gasser, T., Verleger, R., Bacher, P., & Sroka, L. (1988). Development of the EEG for school-age children and adolescents: I. Analysis of band power. *Electroencephalography and Clinical Neurophysiology*, 69, 91–99.
- Gevens, A., Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: Effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, 7, 374–385.
- Gillberg, C. (1993). Autism and related behaviors. *Journal of Intellectual Disability Research*, 37, 343–372.
- Goldstein, G., Johnson, C. R., & Minshew, N. J. (2001). Attentional processes in autism. *Journal of Autism and Developmental Disorders*, 31, 433–440.
- Gomot, M., Bernard, F. A., Davis, M. H., Belmonte, M. K., Ashwin, C., Bullmore, E. T., et al. (2006). Change detection in children with autism: An auditory event-related fMRI study. *Neuroimage*, 29, 475–484.
- Harmony, T., Hinojosa, G., Marosi, E., Becker, J., Rodriguez, M., Reyes, A., et al. (1990). Correlation between EEG spectral parameters and educational evaluation. *International Journal of Neuroscience*, 54, 147–155.
- Harmony, T., Marosi, E., Becker, J., Rodriguez, M., Reyes, A., Fernandez, T., et al. (1995). Longitudinal quantitative EEG study of children with different performances on a reading–writing test. *Electroencephalography and Clinical Neurophysiology*, 95, 426–433.
- Hazlett, E. A., Buchsbaum, M. S., Hsieh, P., Haznedar, M. M., Platholi, J., LiCalzi, E. M., et al. (2004). Regional glucose metabolism within cortical Brodmann areas in healthy individuals and autistic patients. *Neuropsychobiology*, 49, 115–125.
- Haznedar, M. M., Buchsbaum, M. S., Hazlett, E. A., LiCalzi, E. M., Cartwright, C., & Hollander, E. (2006). Volumetric analysis and three-dimensional glucose metabolic mapping of the striatum and thalamus in patients with autism spectrum disorders. *American Journal of Psychiatry*, 163(7), 1252–1263.
- Haznedar, M. M., Buchsbaum, M. S., Metzger, M., Solimando, A., Spiegel-Cohen, J., & Hollander, E. (1997). Anterior cingulate gyrus volume and glucose metabolism in autistic disorder. *American Journal of Psychiatry*, 154, 1047–1050.
- Haznedar, M. M., Buchsbaum, M. S., Wei, T. C., Hof, P. R., Cartwright, C., Bienstock, C. A., et al. (2000). Limbic circuitry in patients with autism spectrum disorders studied with positron emission tomography and magnetic resonance imaging. *American Journal of Psychiatry*, 157, 1994–2001.
- Henderson, H., Schwartz, C., Mundy, P., Burnette, C., Sutton, S., Zahka, N., et al. (2006). Response monitoring, the error-related negativity, and differences in social behavior in autism. *Brain and Cognition*, 61(1), 96–109.
- Hester, R., Fassbender, C., & Garavan, H. (2004). Individual differences in error processing: A review and reanalysis of three event-related fMRI studies using Go/Nogo task. *Cerebral Cortex*, 14, 986–994.
- Hill, E. L., & Russell, J. (2002). Action memory and self-monitoring in children with autism: Self versus other. *Infant and Child Development*, 11(2), 159–170.
- Hong Kong Education Department & Hong Kong Psychological Society. (1981). *The Hong Kong Wechsler Intelligence Scale for children*. Hong Kong: Government Printer (in Chinese).
- Hughes, C., & Russell, J. (1993). Autistic children's difficulty with mental disengagement from an object: Its implications for theories of autism. *Developmental Psychology*, 29, 498–510.
- Hughes, C., Russell, J., & Robbins, T. W. (1994). Evidence for executive dysfunction in autism. *Neuropsychologia*, 32, 477–492.
- Ishii, R., Shinosaki, K., Ukai, S., Inouye, T., Ishihara, T., Yoshimine, T., et al. (1999). Medial prefrontal cortex generates frontal midline theta rhythm. *NeuroReport*, 10, 675–679.
- John, E. R., Prichep, L., Ahn, H., Easton, P., Fridman, J., & Kaye, H. (1983). Neurometric evaluation of cognitive dysfunctions and neurological disorders in children. *Progress in Neurobiology*, 21, 239–290.
- John, E. R., Prichep, L. S., Fridman, J., & Easton, P. (1988). Neurometrics: Computer-assisted differential diagnosis of brain dysfunctions. *Science*, 239, 162–169.

- Johnson, C. P., Myers, S. M., & Council on Children with Disabilities, (2007). Identification and evaluation of children with autism spectrum disorders. *Pediatrics*, *120*, 1183–1215.
- Kana, R. K., Keller, T. A., Minshew, N. J., & Just, M. A. (2007). Inhibitory control in high-functioning autism: Decreased activation and underconnectivity in inhibition networks. *Biological Psychiatry*, *62*, 198–206.
- Kleinmans, N., Akshoomoff, N., & Delis, D. C. (2005). Executive functions in autism and Asperger's disorder: Flexibility, fluency, and inhibition. *Developmental Neuropsychology*, *27*, 379–401.
- Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, *29*, 169–195.
- Kok, A., Ridderinkhof, K. R., & Ullsperger, M. (2006). The control of attention and actions: Current research and future developments. *Brain Research*, *1105*, 1–6.
- Kropotov, J. D., Crawford, H. J., & Polyakov, Y. I. (1997). Somatosensory event-related potential changes to painful stimuli during hypnotic analgesia: Anterior cingulate cortex and anterior temporal cortex intracranial recordings. *International Journal of Psychophysiology*, *27*, 1–8.
- Landry, R., & Bryson, S. E. (2004). Impaired disengagement of attention in young children with autism. *Journal of Child Psychology and Psychiatry*, *45*, 1115–1122.
- Lezak, M. D., Howieson, D. B., & Loring, D. W. (2004). *Neuropsychological assessment* (4th ed.). New York: Oxford University Press.
- Liddle, P. F., Kiehl, K. A., & Smith, A. M. (2001). Event-related fMRI study of response inhibition. *Human Brain Mapping*, *12*, 100–109.
- Lord, C., Rutter, M., DiLavore, P. C., & Risi, S. (2002). *Autism diagnostic observation schedule*. Los Angeles: Western Psychological Services.
- Luna, B., Minshew, N. J., Garver, K. E., Lazar, N. A., Thulborn, K. R., Eddy, W. F., et al. (2002). Neocortical system abnormalities in autism. *Neurology*, *59*, 834–840.
- Mahone, E. M., Koth, C. W., Cutting, L., Singer, H. S., & Denckla, M. B. (2001). Executive function in fluency and recall measures among children with Tourette syndrome or ADHD. *Journal of the International Neuropsychological Society*, *7*, 102–111.
- Menon, V., Adelman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/NoGo response inhibition task. *Human Brain Mapping*, *12*(3), 131–143.
- Miller, J. O., & Low, K. (2001). Motor processes in simple, go/no-go, and choice reaction time tasks: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 266–289.
- Minshew, N. J., Meyer, J., & Goldstein, G. (2002). Abstract reasoning in autism: A dissociation between concept formation and concept identification. *Neuropsychology*, *16*, 327–334.
- Monastera, V. J., Lubar, J. F., & Linden, M. (2001). The development of a quantitative electroencephalographic scanning process for attention deficit-hyperactivity disorder: Reliability and validity studies. *Neuropsychology*, *15*, 136–144.
- Monastera, V. J., Lubar, J. F., Linden, M., VanDeusen, P., Green, G., Wing, W., et al. (1999). Assessing attention deficit hyperactivity disorder via quantitative electroencephalography: An initial validation study. *Neuropsychology*, *13*, 424–433.
- Mundy, P. (2003). Annotation: The neural basis of social impairments in autism: The role of the dorsal medial-frontal cortex and anterior cingulate system. *Journal of Child Psychology and Psychiatry*, *44*, 793–809.
- Murias, M., Webb, S. J., Greenson, J., & Dawson, G. (2007). Resting state cortical connectivity reflected in EEG coherence in individuals with autism. *Biological Psychiatry*, *62*, 270–273.
- Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*, 220–246.
- Nyden, A., Gillberg, C., Hjelmquist, E., & Heiman, M. (1999). Executive function/attention deficits in boys with Asperger syndrome, attention disorder and reading/writing disorder. *Autism*, *3*, 213–228.
- Onton, J., Delorme, A., & Makeig, S. (2005). Frontal midline EEG dynamics during working memory. *Neuroimage*, *27*, 341–356.
- Ozonoff, S., & Jensen, J. (1999). Brief report: Specific executive function profiles in three neurodevelopmental disorders. *Journal of Autism and Developmental Disorders*, *29*(2), 171–177.
- Ozonoff, S., & Strayer, D. L. (1997). Inhibitory function in nonretarded children with autism. *Journal of Autism and Developmental Disorders*, *27*, 59–77.
- Pascual-Marqui, R. D., Lehmann, D., Koenig, T., Kochi, K., Merlo, M. C. G., Hell, D., et al. (1999). Low resolution brain electromagnetic tomography (LORETA) functional imaging in acute, neuroleptic-naïve, first-episode, productive schizophrenia. *Psychiatry Research: Neuroimaging*, *90*, 169–179.
- Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain. *International Journal of Psychophysiology*, *18*, 49–65.
- Pinkerton, F., Watson, D. R., & McClelland, R. J. (1989). A neurophysiological study of children with reading, writing and spelling difficulties. *Developmental Medicine and Child Neurology*, *31*, 569–581.
- Pizzagalli, D. A., Oakes, T. R., & Davidson, R. J. (2003). Coupling of theta activity and glucose metabolism in the human rostral anterior cingulate cortex: An EEG/PET study of normal and depressed subjects. *Psychophysiology*, *40*, 939–949.
- Pizzagalli, D., Pascual-Marqui, R. D., Nitschke, J. B., Oakes, T. R., Larson, C. L., Abercrombie, H. C., et al. (2001). Anterior cingulate activity as a predictor of degree of treatment response in major depression: Evidence from brain electrical tomography analysis. *American Journal of Psychiatry*, *158*, 405–415.
- Posner, M. I., & DiGirolamo, G. J. (1998). Executive attention: Conflict, target detection, and cognitive control. In R. Parasuraman (Ed.), *The attentive brain*. Cambridge, MA: MIT Press.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42.
- Reischies, F. M., Neuhaus, A. H., Hansen, M. L., Mientus, S., Mulert, C., & Gallinat, J. (2005). Electrophysiological and neuropsychological analysis of delirious state: The role of the anterior cingulate gyrus. *Psychiatry Research: Neuroimaging*, *138*, 171–181.
- Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). Oops! Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, *35*, 747–758.
- Rossion, B., & Pourtois, G. (2004). Revisiting Snodgrass and Vanderwart's object pictorial set: The role of surface detail in basic-level object recognition. *Perception*, *33*, 217–236.
- Russell, J., & Jarrold, C. (1998). Error-correction problems in autism: Evidence for a monitoring impairment? *Journal of Autism and Developmental Disorders*, *28*, 177–188.
- Russell, J., & Jarrold, C. (1999). Memory for actions in children with autism: Self versus other. *Journal of Cognitive Neuropsychiatry*, *4*(4), 303–331.
- Russell, J., Jarrold, C., & Hood, B. (1999). Two intact executive capacities in children with autism: Implications for the core executive dysfunctions in the disorder. *Journal of Autism and Developmental Disorders*, *29*(2), 103–112.
- Sauseng, P., Hoppe, J., Klimesch, W., Gerloff, C., & Hummel, F. C. (2007). Dissociation of sustained attention from central executive functions: Local activity and inter-regional connectivity in the theta range. *European Journal of Neuroscience*, *25*, 587–593.
- Schmid, R. G., Tirsch, W. S., & Reitmeir, P. (1997). Correlation of developmental neurological findings with spectral analytical EEG evaluations in pre-school age children. *Electroencephalography and Clinical Neurophysiology*, *103*, 516–527.
- Schmitz, N., Rubia, K., Daly, E., Smith, A., Williams, S., & Murphy, D. G. M. (2006). Neural correlates of executive functions in autistic spectrum disorders. *Biological Psychiatry*, *59*, 7–16.
- Schopler, E., Reichler, R. J., & Renner, B. R. (1998). *The Childhood Autism Rating Scale (CARS)*. Los Angeles: Western Psychological Services.
- Shafritz, K. M., Dichter, G. S., Baranek, G. T., & Belger, A. (2008). The neural circuitry mediating shifts in behavioral response and cognitive set in autism. *Biological Psychiatry*, *63*(10), 974–980.
- Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, *6*, 174–215.
- Somsen, R. J. M., Van-Klooster, B. J., Van-der-Molen, M. W., & Van-Leeuwen, H. M. (1997). Growth spurts in brain maturation during middle childhood as indexed by EEG power spectra. *Biological Psychology*, *44*, 187–209.
- Sturm, H., Fernell, E., & Gillberg, C. (2004). Autism spectrum disorders in children with normal intellectual levels: Associated impairments and subgroups. *Developmental Medicine and Child Neurology*, *46*, 444–447.
- Stuss, D. T., Alexander, M. P., Palumbo, C. L., Buckle, L., Sayer, L., & Pogue, J. (1994). Organizational strategies of patients with unilateral or bilateral frontal lobe injury in word list learning tasks. *Neuropsychology*, *8*, 355–373.

- Stuss, D. T., Binns, M. A., Murphy, K. J., & Alexander, M. P. (2002). Dissociations within the anterior attentional system: Effects of task complexity and irrelevant information on reaction time speed and accuracy. *Neuropsychology*, *16*, 500–513.
- Taylor, S. F., Stern, E. R., & Gehring, W. J. (2007). Neural systems for error monitoring: Recent findings and theoretical perspectives. *Neuroscientist*, *13*, 160–172.
- Thakkar, K. N., Polli, F. E., Joseph, R. M., Tuch, D. S., Hadjikhani, N., Barton, J. J. S., et al. (2008). Response monitoring, repetitive behaviour and anterior cingulate abnormalities in autism spectrum disorders (ASD). *Brain*, *131*, 2464–2478.
- Van Veen, V., Cohen, J. D., Botvinick, M. M., Stenger, V. A., & Carter, C. S. (2001). Anterior cingulate cortex, conflict monitoring, and levels of processing. *Neuroimage*, *14*, 1302–1308.
- Wing, L. (1997). The autistic spectrum. *Lancet*, *350*, 1761–1766.