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# Effect of Attentional State on Frequency Discrimination: A Comparison of Children With ADHD On and Off Medication

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Debate continues over the hypothesis that children with language or literacy difficulties have a genuine auditory processing deficit. Several recent studies have reported deficits in frequency discrimination (FD), but it is unclear whether these are genuine perceptual impairments or reflective of the comorbid attentional problems that exist in many children with language and literacy difficulties. The present study investigated FD in children with attention deficit hyperactivity disorder (ADHD) when their attentional state was altered with stimulant medication. Auditory thresholds were obtained using FD and frequency modulation detection (FM) tasks. In the FD task, participants judged which of 2 pairs contained a high–low frequency sound, and in the FM task, children judged which of two tones “wobbled” (i.e., modulated). Children with ADHD had significantly poorer and more variable FD performance when off compared to on stimulant medication, and did significantly worse than controls on all FD runs when off but not on stimulant medication. However, children with ADHD did not differ from controls on the FM task. These findings demonstrate that certain auditory discrimination tasks are influenced by the child’s attentional status. In addition, significant relationships between FD and measures of language and reading were abolished when comorbid attentional difficulties were taken into account. The study has implications for design and interpretation of studies investigating links between auditory discrimination and difficulties in language and literacy.

**KEY WORDS:** ADHD, frequency discrimination, stimulant medication

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When a child has learning difficulties affecting language or literacy, it is important to establish whether these might be caused by perceptual problems in discriminating auditory stimuli. Over the past few decades, a large body of research has demonstrated that a subset of children with specific language impairment (SLI) or developmental dyslexia do poorly on tests that involve discriminating nonverbal sounds that differ in frequency. Although initial work argued that such difficulties were most evident when sounds were brief or occurred in rapid succession (Tallal, 1976, 1980), more recent studies have reported deficits in frequency discrimination (FD), even when there is no time pressure (Ahissar, Protopapas, Reid, & Merzenich, 2000; Amitay, Ahissar, & Nelken, 2002; Cacace, McFarland, Ouimet, Schrieber, & Marro 2000; Hill, Hogben, & Bishop, 2005; McAnally & Stein, 1996; McArthur & Bishop, 2004; Mengler, Hogben, Michie, & Bishop, 2005).

However, auditory discrimination deficits in SLI and dyslexia are not always seen (e.g., Breier, Gray, Fletcher, Foorman, & Klaas, 2002; Norrelgen, Lacerda, & Forssberg, 2002) and the causal importance of any such deficits remains unclear (Halliday & Bishop, 2006). Some argue that poor auditory discrimination affects language and literacy learning by impairing children's acquisition of phonological categories (e.g., Tallal, 2000). However, others have questioned this view, suggesting instead that poor auditory discrimination is a correlated feature of language/literacy problems that has no direct causal influence on children's phonological development (see Bailey & Snowling, 2002, and McArthur & Bishop, 2001, for review). A specific proposal is that children with language/literacy problems do poorly on tests of auditory discrimination because of nonauditory difficulties with task demands. One possibility raised by Breier, Fletcher, Foorman, Klaas, and Gray (2003) is that the association between language-learning difficulties and poor auditory discrimination could be artefactual, with elevated thresholds arising because of fluctuating attention rather than a genuine inability to hear differences between sounds. No one study design is satisfactory for testing this idea, but converging evidence may be obtained from six different kinds of comparison.

## **1. Comparison of Auditory Discrimination Tasks With Control Tasks**

Traditionally, the design of studies of auditory discrimination has involved comparing performance on different tests with similar task demands. The implicit logic is that if children do poorly relative to controls on task A, but not on control task B, then we can rule out general factors such as weak attention as causing the deficit. For instance, Tallal and Piercy (1973) showed that children with SLI did much worse than controls when discriminating tone pairs of different frequency at rapid presentation rates but performed at comparable levels to controls at slow rates. Since both rapid and slow tones were presented in the same task, one might conclude that poor attention could not be responsible for the selective deficit at rapid rates. However, this may not be a valid argument, because all children found the slow rates much easier than the fast rates, and performance was close to ceiling when slow rates were used (see McArthur & Bishop, 2001, for further discussion of this point).

## **2. Investigation of Performance Variability on Repeated Testing**

Because it can be difficult to maintain children's interest in psychoacoustic tasks, studies of clinical groups often rely on relatively brief test sessions when

estimating auditory thresholds in discrimination tasks. However, when children's thresholds are repeatedly estimated on different occasions, it is clear that thresholds can fluctuate widely from one test session to another. The specific pattern of results appears to depend on both the specific auditory task and the age of the children, but tasks that involve discrimination of temporal or spectral characteristics of auditory stimuli often show high variability in children under the age of 8 years (Sutcliffe & Bishop, 2005; Wightman, Allen, Dolan, Kirstler, & Jamieson, 1989). This reinforces concerns that auditory discrimination thresholds obtained with young or learning-disabled children may not provide an accurate estimate of their perceptual abilities but may be influenced by nonauditory factors. This is a particular issue with children who are diagnosed with attention deficit hyperactivity disorder (ADHD), who are characterized by transient but frequent lapses of intention and attention leading to moment-to-moment variability and inconsistency in performance (Castellanos & Tannock, 2002).

## **3. Simulation of Attentional Lapses in Psychophysical Tasks**

Wightman et al. (1989) investigated threshold variation in children using simulated runs on a psychoacoustic task in which the child responded at random on a proportion of trials. It was shown that elevated thresholds could be produced from inattention on far fewer than 50% of trials. Monte Carlo simulations suggested that the adult-child differences and the large between-subjects' variability might have resulted from the influence of factors such as inattention, forgetting, or confusion. They noted that occasional random responding could lead to a similar profile seen in young children when adaptive methods were used to establish psychoacoustic thresholds, with variable thresholds from session to session. More recently, Roach, Edwards, and Hogben (2004) adopted a similar approach to model distributions of psychoacoustic thresholds obtained in samples of participants with dyslexia. Through simulations of the effect of errant or inattentive trials on psychophysical performance, similar patterns of variability were found to those seen in groups of participants with dyslexia. They concluded that general, nonsensory difficulties might be a plausible explanation for auditory discrimination deficits seen in such cases.

## **4. Performance on Auditory Discrimination Tasks Considered in Relation to Explicit Measures of Attention**

McArthur and Bishop (2004) tested young people aged 12 to 21 years with SLI and a typically developing

control group, and considered whether poor FD was related to two measures of attentional skills taken from a standardized test battery, the Test of Everyday Attention for Children (TEA-Ch; Manly, Robertson, Anderson, & Nimmo-Smith, 1998). One subtest assessed sustained auditory attention by requiring the child to count laser-gun sounds that occurred at irregular intervals, and the other assessed control of attention, including inhibition of a prepotent response, in a Stroop-like paradigm. Neither test differentiated participants with SLI who had good or poor FD performance, suggesting that weak attention as assessed on these tests could not explain elevated thresholds that were seen in a subset of the SLI group.

## 5. Auditory Discrimination in Children With ADHD

According to the *Diagnostic and Statistical Manual of Mental Disorders—Fourth Edition (DSM-IV;* American Psychiatric Association, 1994), ADHD affects the ability to regulate activity (hyperactivity), inhibit behavior (impulsivity), and focus attention on a task (inattention) in a developmentally appropriate manner. An early study by Ludlow, Cudahy, Bassich, and Brown (1983) questioned the causal nature of the link between auditory discrimination deficits and language/literacy problems by demonstrating similar poor levels of performance in boys with a diagnosis of hyperactivity who had no observable language impairment. This raised the possibility that any link between auditory and language/literacy problems might be mediated by comorbid attentional problems. This question was taken up by Breier et al. (2001), who compared verbal and nonverbal auditory discrimination tasks in children with reading disability (RD) and controls. Around half the RD group had comorbid ADHD. Poor auditory discrimination on these tasks was found in both the RD groups, indicating that it could not be explained away by comorbid ADHD. However, significant correlations were found between auditory discrimination and literacy tasks only for children without ADHD. The authors concluded that the role of ADHD needs to be taken into account in studies of auditory perception in children with RD. However, in a subsequent study, Breier et al. (2002) found no deficits on a nonverbal task based on Tallal's rapid auditory processing test when they compared RD children with a control group, regardless of ADHD status. Breier et al. (2003) used tasks assessing the perception of auditory temporal and nontemporal cues in children with (a) RD without ADHD, (b) ADHD alone, (c) RD and ADHD, and (d) no impairments. The presence of RD was associated with impairment in detection of a tone onset time asynchrony. The presence of ADHD resulted in a general reduction of performance across psychoacoustic tasks. There was

no significant difference in the degree of deficit between the auditory temporal and nontemporal tasks. Thus, although it could not totally account for deficits in children with RD, ADHD appeared to be a potentially significant factor in children's psychoacoustic performance. The authors commented that the impulsive behavior in children with ADHD-combined type might result in increased variability in performance and a greater number of trials to reach an accurate threshold. However, they used a single adaptive run to estimate thresholds and so were not able to measure the amount of variability in task performance.

## 6. Assessment of Auditory Abilities in Children With ADHD When On and Off Medication

Central nervous stimulant medications raise the level of activity, arousal, or alertness of the central nervous system (CNS) through mimicking the action of neurotransmitters (i.e., dopamine, norepinephrine). Three frequently used stimulants are dextroamphetamine (Dexedrine), methylphenidate (Ritalin), and magnesium pemoline (Cylert) (DuPaul, Barkley, & Connor, 1998). Dextroamphetamine enhances catecholamine activity in the CNS, through increasing the availability of norepinephrine and/or dopamine in the synaptic cleft. It has been suggested that by increasing extracellular dopamine levels, methylphenidate activates the motivational circuits and makes tasks more enjoyable (Volkow et al. 2001). Volkow and colleagues found methylphenidate suppressed the background firing of neurons not associated with a task. This made the brain transmit a clearer signal, accentuated specific activation, and increased a child's focus. At the behavioral level, stimulant medications provide beneficial effects on a range of clinically relevant domains, including parent and teacher behavior ratings (Barkley, 1991), academic productivity and accuracy (Elia, Welsh, Gullotta, & Rapoport, 1993), and fidgetiness and motor restlessness (DuPaul, Barkley, & McMurray, 1994).

In 1996, the American Speech-Language-Hearing Association (ASHA) recommended investigations concerning the effects of stimulant medication on auditory processing function, and a handful of studies have adopted this approach (Cook et al., 1993; Dalebout, Nelson, Hietko, & Frentheway, 1991; Keith & Engineer, 1991; Tillery, Katz, & Keller, 2000). However, in general, their focus has been on standardized tests used to diagnose central auditory processing disorder (APD) in children. Most of these tests use verbal materials and so cannot address the issue of whether attentional manipulations affect psychoacoustic thresholds on the kinds of nonverbal auditory abilities that have been implicated in dyslexia and SLI.

## Aims of the Current Study

The literature to date suggests that children's attentional status may be an important influence on their auditory discrimination performance, but the effect may vary from one task to another, depending on the precise nature of the discrimination being made, and may also be affected by age. It remains unclear just how far attentional fluctuations could explain elevated thresholds in some clinical groups. We aimed to throw light on this issue.

In the current study we adopted a novel methodological approach that combined features from several previous studies. Like Breier et al. (2001, 2002, 2003), we compared auditory discrimination skills in children with ADHD and control children, but our main focus was on a within-group rather than between-groups comparison, namely to compare auditory FD in children with ADHD when on and off stimulant medication. We were not in a position to investigate medication-specific physiological effects: The children we studied took a range of medications, but in all cases we had evidence that their ADHD symptoms were well controlled by medication. As reported by Sutcliffe, Bishop, and Houghton (2006), we took a wide range of conventional measures of attention, including parent and experimenter ratings and standardized tests of different aspects of attention, and demonstrated that the medication manipulation was effective in modifying scores on these.

In referring to attention, we note that this is not a unitary construct, and experts disagree as to whether the core deficit in ADHD should be conceptualized as involving executive functions more broadly and/or motivational factors (e.g., Barkley, 1997, 2003). We return to the issue of what cognitive factors are influenced by stimulant medication in the Discussion section.

We focused on FD because this is a nonverbal auditory skill that has recently been linked to both reading and language impairment, but which also appears especially sensitive to attentional factors (Sutcliffe & Bishop, 2005). We used a child-friendly task taken from Sutcliffe and Bishop (2005) that did not require the child implicitly to label the stimuli as high or low, but simply to judge whether two tones in a pair were same or different, with appropriate reinforcement and feedback in order to provide optimal conditions to examine auditory performance. In addition, the use of a touch screen allowed the assessment of speed of responses for each child. Furthermore, we obtained repeated estimates of auditory thresholds, making it possible to look at variability as well as mean level of performance. We also contrasted performance on FD with that on a control task of frequency modulation (FM) detection that incorporated many similar task demands.

Our main predictions were (a) that unmedicated children with ADHD would obtain higher (i.e., worse) and more variable thresholds on the auditory FD task than control children, and (b) that auditory thresholds in children with ADHD would improve when they received medication that improved their poor attention.

In a previous paper, we reported the effects of medication in this sample on measures of attention, language, and literacy (Sutcliffe et al., 2006). In the current report, we had the subsidiary aim of examining the relationship between auditory discrimination on the one hand and language and literacy skills on the other hand, to consider, first, whether significant relationships were obtained between these domains and, second, whether such relationships remained significant when measures of attentional status were partialled out.

## Method Participants

The sample consisted of 36 children (26 male and 10 female) aged 6;1 (years;months) to 11;9 ( $M = 98.53$  months,  $SD = 18.17$ ) recruited from a large urban area in Perth, Western Australia. Study participants were required to have English as the only language spoken in the home; have no medical problems relating to hearing, speech, or language; and pass an auditory screening for pure tones of 0.5, 1.0, 2.0, and 4.0 kHz presented at 25 dB HL in one or both ears. There were 18 children with a clinical diagnosis of ADHD and 18 matched controls. Children in the ADHD group had all been diagnosed by a consultant pediatrician as meeting *DSM-IV* (American Psychiatric Association, 1994) criteria for ADHD on the basis of a clinical interview, and had subsequently been assessed by a clinical psychologist who confirmed that there were no other comorbid learning disabilities. All children with ADHD had been receiving medication for at least 3 months prior to the study. Because the focus of this study concerned whether performance was influenced by medication that controlled ADHD symptoms, we did not require that all children took the same type of medication. Two children were taking methylphenidate (Ritalin), 14 children were taking dextroamphetamine (Dexedrine), and 2 children were taking both Ritalin and clonidine hydrochloride (Catapres). The amounts being prescribed differed (5–40 mg), as did length of time since the stimulant medication was prescribed (3 months to 4 years). The critical factor for this study was that we could show in all cases that the medication led to significant improvement in ADHD symptoms, both by parental report and standardized tests (Sutcliffe et al., 2006).



The typically developing control group was recruited from one Perth primary school. An information letter and consent form were sent to the parents of all children in Grades 2–7, resulting in a 25% (38 out of 150) response rate. Each child in the ADHD group was individually matched on age with a control child. Control children nearest in age to the children with ADHD were selected (maximum of 5 months separating ADHD and age-matched controls,  $M = 1.9$  months,  $SD = 1.6$ ). Individual matching was used because it decreases the error variance and prevents matching variables from becoming competing causal factors of any effects (Kirk, 1995). All children in the control group had undergone annual school screening for literacy problems, and none of those selected had been identified as having any learning disability.

## Procedure

As the auditory psychophysical tasks did not involve listening for stimuli of low intensity, we did not test children in soundproofed conditions, but rather used a quiet room at the university (for children with ADHD) or school (for controls), with stimuli presented through sound-attenuating headphones. This is comparable to previous procedures adopted by other researchers working with typically developing child samples (e.g., De Weirtdt, 1988; Fischer, personal communication, January 24, 2005; Sutcliffe & Bishop, 2005; Talcott, personal communication January 21, 2005). Sessions were separated in almost all cases by 14 days (range = 14–24 days,  $M = 14.94$ ). The time of day was kept constant in both sessions. The control children were tested at their primary school over two sessions, separated in most cases by 14 days (range = 10–16 days,  $M = 13.78$ ).

For the children with ADHD, one session was conducted on medication and one off medication. The order of these sessions was counterbalanced across the group. For the medicated session (Session M), parents were instructed to give the medication to their child at the same time they would on a typical day. Sessions were arranged so that testing commenced no longer than 2 hr after ingestion of the medication. For the nonmedicated session (Session N), no medication was administered to the child on the afternoon or evening prior to the testing session, resulting in a minimum of 20 hr medication free. Parents were contacted the day before testing to remind them of this, and compliance with instructions was verbally confirmed prior to each test session.

Children in the typically developing control group received no medication, but sessions were nevertheless designated as Session M and Session N for comparison with the matched ADHD group. Thus, if a child with ADHD had the medicated session and then the non-medicated session, the matched control child would have

the first session designated as Session M and the second session designated as Session N. This made it possible to compare the control and ADHD groups in a single analysis of variance (ANOVA) while controlling for any effects of practice.

## Psychometric Tests of Ability, Attention, Language, and Literacy

The psychometric test battery is detailed by Sutcliffe et al. (2006) and is described only briefly here. Children were given the Vocabulary and Matrices subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) as measures of verbal and nonverbal ability, respectively; the Children's Test of Nonword Repetition (CNRep; Gathercole & Baddeley, 1996) and the Recalling Sentences subtest of the Clinical Evaluation of Language Fundamentals—UK 3 (CELF–3 UK; Semel, Wiig, & Secord, 1995), which are both sensitive markers of SLI (Conti-Ramsden, Botting, & Faragher, 2001); and the Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999), to measure literacy. Finally, in each session both groups of children completed four subtests of the Test of Everyday Attention for Children (TEA-Ch; Manly et al., 1998) in the following order: Score!, Same Worlds, Opposite Worlds, and Walk Don't Walk. The TEA-Ch subtests assessed the ability to sustain attention to auditory stimuli (Score!, Walk Don't Walk), attentional control (Same Worlds, Opposite Worlds), and response inhibition to action (Walk Don't Walk).

## Auditory Psychophysical Tasks

*FM (Sessions M and N).* This task was included to familiarize children with basic task demands using a relatively easy auditory discrimination task. Previous work with typically developing children had shown that 6-year-olds found this an easy task to understand, and usually performed well above chance (Sutcliffe & Bishop, 2005). The FM task was completed once in each session, before the FD tasks were given.

The task required a participant to discriminate an unmodulated from a frequency-modulated tone using a two-interval, two-alternative forced choice paradigm. The modulation depth was adaptively altered using a "more virulent PEST" procedure (Findlay, 1978). This involves presenting very easy discriminations initially and using large step sizes to increase difficulty level until an error is made. When an error is made, the discrimination is made easier (i.e., a reversal in the direction of the track occurs). Step size is progressively halved, until a threshold level is reached at which the participant attains 75% correct on the psychometric

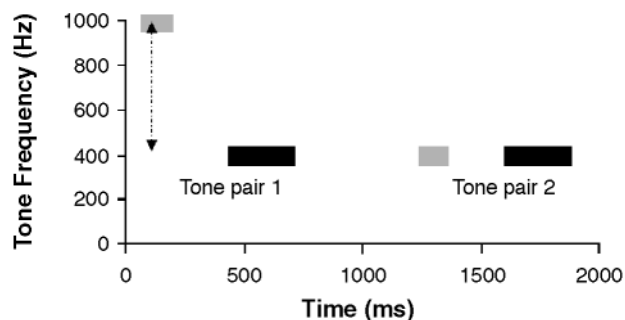
function. The procedure continues to converge until a stable threshold is obtained. The task was stopped after 10 reversals had occurred or a maximum of 80 trials had been completed. The threshold was taken as the average target frequency across the last four reversals in the adaptive track.

The tones were 1,000 ms in duration and presented to both ears at a comfortable level through Sennheiser 25 headphones. The two intervals were separated with a 500 ms interstimulus interval (ISI). The unmodulated tone had a constant frequency of 0.4 kHz. The modulated tone had a carrier frequency of 0.4 kHz and was sinusoidally varied at a 20 Hz rate. The tones were gated on and off with a 10 ms rise–fall times. The maximum step size was 9 Hz and minimum step size was 0.75 Hz. The initial modulation depth was 74.25 Hz. The stimuli were generated using a Tucker-Davis Technologies System II.

For each trial, two dinosaurs appeared on the screen, one on the left and the other on the right, and in front of each dinosaur was a colored ball. A trial consisted of each dinosaur colliding into its ball, resulting in a modulated tone (the target tone) being produced by one dinosaur and an unmodulated tone being produced by the other. The interval containing the modulated tone was randomly allocated across each trial. Using a touch screen monitor connected to a laptop computer, the participant touched the ball that produced the “wobbly noise” (i.e., the modulated tone). The experimenter played examples of the modulated tones, after which eight practice trials commenced. If the participant correctly responded to a minimum of six out of eight practice trials, with a minimum of 5 trials being consecutively correct responses, the test trials began. Correct identification of the modulated tone was reinforced with small colorful pictures on the screen and a cheerful noise, and wrong answers with a cross and a sigh noise. Note that the task was unpaced to minimize the likelihood of a child missing a trial through inattention. The experimenter sat on a chair next to the child and waited until the child was looking straight ahead at the screen before initiating a trial. The latency of the child’s response was obtained for each trial.

**FD (Sessions M and N).** The paradigm was based on prior work with typically developing children by Sutcliffe and Bishop (2005). Three FD threshold estimates were obtained on each test occasion, with the psychoacoustic tasks interleaved with psychometric tasks to minimize boredom and fatigue. The FD task used a four-interval, two-alternative task that was analogous to that used in the FM task, except that the listener made judgements about two pairs of tones. Whereas in the FM task, in which children judged which tone wobbled, in the FD task they judged which pair contained a “cuckoo” sound (i.e., an initial higher tone followed by a 400 Hz tone). The

**Figure 1.** A schematic illustration of a frequency discrimination (FD) trial: The target (gray box) and comparison (black box) tone pair are shown. The arrow represents the changing of target tone frequency using the virulent PEST procedure. In this example the higher target tone is located in Tone Pair 1.



other pair of two tones was of the same frequency (400 Hz). Thus, the child could succeed by identifying the pair in which the two tones were different from one another, without needing implicitly to label tones as high or low.

For each pair, the first tone was designated the target tone and the second tone the comparison tone. The target tones, one of 400 Hz and the other of higher frequency, were 50 ms in duration. Each was followed after 320 ms by a 200 ms comparison tone of 400 Hz. The higher frequency tone ranged from 1000 Hz to 400 Hz. The target tones were gated with a 10 ms cosine-squared rise–fall time, and the comparison tones were gated with a 20 ms cosine-squared rise–fall time. A schematic illustration of these details is provided in Figure 1.

The maximum step size used in the PEST algorithm was 64 Hz and the minimum step size was 2 Hz. Like the FM task, the FD task was stopped after 10 reversals had occurred or a maximum of 80 trials had been completed. The threshold was taken as the average target frequency across the last four reversals in the adaptive track.

An interval of 500 ms separated the two pairs of tones. An additional silent gap of 100 ms preceded the target tone in both tone pairs, resulting in each trial lasting 1,840 ms in both target conditions. The computer program was modified so that different pictured animals were used in the program on each of the three runs in a session, to make the task more interesting.

As in the FM task, the PEST procedure was set to converge on the 75% correct point. The threshold was taken as the average target frequency across the last four reversals in the adaptive track. In addition, three measures of performance variability were taken. Within-run variability was assessed by taking the standard deviation

**Table 1.** Mean (*SD*) standard scores for the psychometric tests when medicated (Session M) and nonmedicated (Session N) for the ADHD and control groups.

Tasks	ADHD ( <i>N</i> = 18)	Controls ( <i>N</i> = 18)	<i>t</i>	<i>p</i>
Session M				
WASI Vocabulary	44.61 (10.87)	45.44 (8.11)	−0.261	<i>ns</i>
WASI Matrix Reasoning	47.50 (9.24)	52.11 (10.19)	−1.423	<i>ns</i>
CELF–3 UK Recalling Sentences	5.28 (2.52)	10.11 (2.51)	−5.761	<.001
CNRep <sup>a</sup>	98.62 (15.11)	106.00 (12.55)	−1.355	<i>ns</i>
TOWRE				
Sight Word Efficiency	94.22 (14.70)	112.11 (13.81)	−3.764	<.001
Phonetic Decoding Efficiency	94.11 (12.79)	112.33 (14.94)	−3.931	<.001
TEA-Ch				
Score!	9.17 (3.81)	10.72 (3.86)	−1.217	.232
Same Worlds	9.56 (3.32)	11.89 (3.20)	−2.145	.039
Opposite Worlds	9.33 (3.58)	11.33 (3.63)	−1.664	.105
Walk Don't Walk	7.17 (2.55)	10.83 (2.98)	−3.970	<.001
Session N				
TOWRE				
Sight Word Efficiency	93.89 (14.52)	113.50 (13.89)	−4.142	<.001
Phonetic Decoding Efficiency	93.06 (12.75)	111.67 (13.36)	−4.275	<.001
TEA-Ch				
Score!	6.50 (3.15)	11.00 (3.12)	−4.304	<.001
Same Worlds	7.39 (2.91)	12.00 (3.41)	−4.360	<.001
Opposite Worlds	6.89 (3.74)	11.68 (3.26)	−4.096	<.001
Walk Don't Walk	6.00 (2.83)	10.39 (3.20)	−4.359	<.001

*Note.* Session was categorized according to medication status of ADHD group; controls were unmedicated in both sessions. ADHD = attention deficit/hyperactivity disorder; WASI = Wechsler Abbreviated Scale of Intelligence; CELF–3 UK = Clinical Evaluation of Language Fundamentals—UK 3; CNRep = Children's Test of Nonword Repetition; TOWRE = Test of Word Reading Efficiency; TEA-Ch = Test of Everyday Attention for Children

<sup>a</sup>*N* = 13 because standardized scores on the CNRep are only provided for children up to the age of 9 years; this excluded 5 children in each group.

of the target frequency across the last four reversals of the PEST procedure, with a low value reflecting smooth convergence on the threshold. Between-runs variability was the standard deviation of the three threshold estimates within a session. High between-runs variability could reflect erratic performance, but it could also indicate improvement with practice. Therefore, a further measure of between-runs performance was devised to identify those children whose thresholds deteriorated across the three runs. This subtracted Run 2 from Run 1, Run 3 from Run 1, and Run 3 from Run 2, and calculated the maximum of these three values. Note that a positive value indicated a higher threshold (i.e., worse performance) on a later run, whereas sustained improvement across the three runs corresponded to a negative value.

## Results

### Tests of Ability and Attention

Performance on the psychometric tests and on the attentional measures when on and off stimulant medication

is reported in Sutcliffe et al. (2006). Mean scores are summarized in Table 1 and show that medication affected performance on attentional measures in children with ADHD but did not affect scores on the TOWRE.

### Auditory Psychophysical Performance

**FM.** FM thresholds were obtained in both sessions. All children performed better than chance level (binomial  $p < .05$ ). Table 2 shows thresholds (modulation depth) in Hertz and also converted into a frequency modulation index (FMI), which divides thresholds in Hertz by the FM rate, to facilitate comparison to other studies (e.g., Talcott et al., 1999).

To examine the FM performance in children with ADHD and control children using the FMI data, a mixed ANOVA was conducted with one between-subjects factor (group) and one repeated measure (session: M or N). This showed no significant effect of session,  $F(1, 34) = 0.034$ ,  $p = .86$ , or group,  $F(1, 34) = 0.199$ ,  $p = .66$ , and no significant Session  $\times$  Group interaction,  $F(1, 34) = 0.018$ ,  $p = .89$ .

**Table 2.** Mean (SD) thresholds, response times, and variability indices for the frequency modulation (FM) and frequency discrimination (FD) tasks for the ADHD and control group in Sessions M and N.

	ADHD				Control			
	Session M		Session N		Session M		Session N	
	M	SD	M	SD	M	SD	M	SD
FM								
Threshold: Modulation depth (Hz)	2.0	2.2	2.1	1.5	2.3	2.1	2.5	4.2
Threshold: FMI	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Response time (ms)	863.4	355.2	1027.3	374.3	1052.5	341.9	990.7	524.6
FD								
Threshold ( $\Delta f$ Hz, avg. 3 runs)	131.1	140.2	239.4	149.3	42.7	77.6	28.9	37.8
Response time (ms, avg. 3 runs)	912.9	274.4	1268.4	595.9	1005.3	279.7	970.5	315.5
Within-run variation (Hz) <sup>a</sup>	17.9	17.8	11.5	9.5	4.9	4.8	9.7	16.1
Between-runs variation (Hz) <sup>b</sup>	96.0	89.1	152.1	105.6	30.8	61.2	26.1	50.1
Maximum deterioration (Hz)	-18.4	48.6	211.5	214.0	36.4	79.1	11.9	26.4

Note. FMI = frequency modulation index.

<sup>a</sup>Standard deviation of the presentation level across the last four reversals during the PEST procedure. <sup>b</sup>Standard deviation of the threshold obtained for three runs.

To examine the speed of response for the FM task for each group across both sessions, a mixed ANOVA was conducted with one between-subjects factor (group) and one repeated measure (session: medicated or non-medicated). This showed no significant effect of session,  $F(1, 34) = 0.27, p = .605$ , and no significant effect of group,  $F(1, 34) = 0.67, p = .420$ .

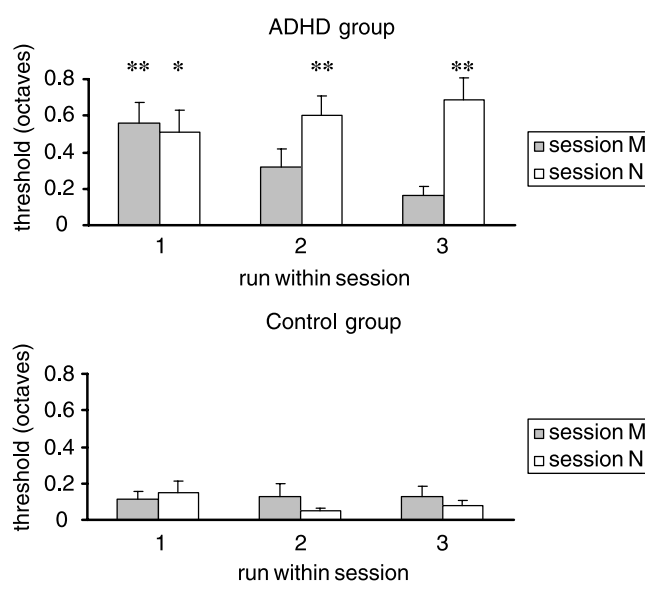
Therefore, the ability to discriminate an unmodulated from a modulated frequency tone was completed to a comparable level in both groups and was not affected by medication status in the ADHD group.

**FD.** All children reached criteria for continuation during practice trials, and no child scored consistently at chance level in all subsequent runs.

Frequency thresholds were log-transformed into octaves to reduce group differences in variance. Although the transformation reduced these differences in variance, it was not abolished, so assumptions of ANOVA were not met. It is important, therefore, that the following results are recognized as being conservative. The use of ANOVA was still considered the most appropriate in terms of robustness and for the analysis of equality of means given the amount of variability. Although not resolving this failure of assumptions for ANOVA, it should be noted that subsequent post hoc  $t$  tests were adjusted for unequal variance. Mean thresholds on the FD task are shown in Figure 2. To examine the performance of children with ADHD and controls on the FD runs across the sessions, a mixed ANOVA was conducted with one between-subjects factor (group) and two repeated measures: run (1, 2, or 3) and session (M or N). This showed a significant effect of session,  $F(1, 34) = 6.54, p < .015$ , and

group,  $F(1, 34) = 21.00, p < .001$ . There was no significant effect of run,  $F(2, 68) = 1.62, p = .205$ . There was a significant interaction of Session  $\times$  Group,  $F(1, 34) = 11.18, p < .002$ ; Session  $\times$  Run,  $F(1.68, 57.06) = 4.03, p < .029$ ; and Session  $\times$  Run  $\times$  Group,  $F(1.68, 57.06) = 7.74, p < .002$ .

**Figure 2.** Mean thresholds on the FD task for ADHD and control groups across three runs of Sessions M and N. Note: significant differences in thresholds on each condition between children with ADHD and controls using a  $t$  test adjusted for unequal variance are indicated by \* at the .05 level and \*\* at the .01 level.





Inspection of Figure 2 suggests that neither session nor run had any effect on thresholds of control children, and this was confirmed by a supplementary two-way repeated measures ANOVA on the control group only, which gave no significant main effects. As is evident from Figure 2, within the ADHD group, there was a significant interaction between session and run, such that performance improved across runs in Session M, but not in Session N, where the trend was for performance to deteriorate. Using pairwise *t* tests, thresholds in Session M and N were significantly different on the second and third runs for children with ADHD, but not on the first run, nor on any runs for the control children between sessions. Furthermore, the results were not affected by the order of presentation of tasks across session (i.e., there were no significant differences between thresholds regardless of whether the Session M or Session N was completed first or second).

To examine the speed of response for the FD task, a mixed ANOVA was conducted with group as the between subjects factor and session (M or N) as the repeated measure. This showed a significant effect of session,  $F(1, 34) = 4.684, p = .038$ , but no significant effect of group,  $F(1, 34) = 0.93, p = .343$ . There was a significant Session  $\times$  Group interaction,  $F(1, 34) = 6.94, p = .013$ . As can be seen from the means in Table 2, the responses of the ADHD group were slower than those of controls in Session N only, but this failed to reach significance,  $t(25.8) = 1.88, p = .072$ , when adjusted for unequal variances.

## Performance Variability on the FD Task

*Within-run variation.* The standard deviation of the target frequency across the last four reversals of the PEST procedure was used to index performance variability within a run (see Table 2). A single mixed ANOVA on these scores showed no significant effect of session,  $F(1, 34) = 0.086, p = .771$ ; a significant effect of group,  $F(1, 34) = 4.67, p = .038$ ; and a marginal Session  $\times$  Group interaction,  $F(1, 34) = 4.10, p = .051$ . The trend in the data went contrary to prediction, insofar as there was a tendency for greater variability in the ADHD group in Session M than Session N. This did not reach significance on a paired samples *t* test,  $t(17) = 1.75, p = .098$ .

*Between-runs variation.* In each session, three estimates of the threshold were obtained. The standard deviation of these three estimates gave an indication of the stability of the child's threshold with a single test session. An ANOVA on this measure revealed no significant effect of session,  $F(1, 34) = 1.57, p = .219$ ; a significant effect of group,  $F(1, 34) = 19.60, p = .001$ ; and no significant Session  $\times$  Group interaction,  $F(1, 34) = 1.99, p = .168$ . Thus, between-runs variability was greater in the ADHD group, regardless of medication status.

**Table 3.** Correlations between the FD tasks, reading, and language measures when age is partialled out (above diagonal) and when age and the attention composite is partialled out (below diagonal) for the whole sample.

	FD Session M	FD Session N	TOWRE average	Recalling Sentences	CNRep
FD Session M	—	.61**	-.50**	-.36*	-.42*
FD Session N	.50**	—	-.42*	-.53**	-.34*
TOWRE average	-.29	.026	—	.71**	.56**
Recalling Sentences	-.09	-.26	.28	—	.57**
CNRep	-.26	-.10	.29	.34	—

Note. The shaded cells remain significant at .014 level after correction for multiple comparisons.

\* $p < .05$  level. \*\* $p < .01$  (two-tailed).

*Maximum deterioration.* Another measure of between-runs performance was devised to identify those children whose thresholds deteriorated across the three runs. This subtracted Run 2 from Run 1, Run 3 from Run 1, and Run 3 from Run 2, and calculated the maximum of these three values. An ANOVA on these scores gave a significant effect of session,  $F(1, 34) = 15.41, p = .001$ , and group,  $F(1, 34) = 5.00, p = .032$ , and a significant Session  $\times$  Group interaction,  $F(1, 34) = 23.56, p = .001$ . The mean scores for control children and for the ADHD medicated session were close to zero but, as predicted, the children with ADHD had significantly larger maximum deterioration when off compared to on medication,  $t(17) = -4.68, p = .001$ .

## Correlations Between Psychometric and Auditory Psychophysical Measures

Relationships between the psychometric and psychophysical tasks were examined by forming several composite measures. The TEA-Ch raw scores were transformed into *z* scores and averaged. The three FD runs in each session were averaged.

Table 3 shows the correlations between the FD thresholds and language and literacy measures for the whole sample first with just age partialled out (above the diagonal) and then with both age and the TEA-Ch composite partialled out (below the diagonal). When TEA-Ch was not taken into account, there were significant correlations between most of the language and literacy scores and the FD thresholds. None of these remained significant when scores on the TEA-Ch were taken into consideration.

## Discussion

The study examined the effect of stimulant medication on FD performance in children with ADHD. Key

findings were that (a) children with ADHD were able to detect very small modulated frequencies but had poor FD, and were more susceptible to deterioration with practice; (b) the overall FD performance in the children with ADHD was significantly better when on compared to off stimulant medication, converging with control levels of performance after the first run in a session; (c) children with ADHD were significantly poorer than the age-matched controls on all FD runs when off stimulant medication; (d) children with ADHD were more inconsistent on the FD runs when off compared to on stimulant medication, in comparison to the control children who improved with practice, or had consistent performance across the three FD runs in each session; and (e) children with ADHD had a slower speed of response with larger standard deviations on the FD task when off compared to on stimulant medication.

## ***Limitations of the Study***

Because we did not have any control over the type or dosage of stimulant medication that the children with ADHD were taking, we cannot speculate about neuropharmacological mechanisms that are involved in the improved thresholds of children when on medication. We could see no evidence of differences in effects of the various medications, either on ratings of symptoms or on auditory discrimination, but the numbers were too small to apply valid statistical tests. It should be noted that our design did ensure that each child was taking medication that had been identified as clinically effective for their individual needs.

Another limitation of this study was the lack of blinding to the child's medication status. An improvement to the procedure would be to use a placebo rather than removing the stimulant medication in Session N. This would remove the possibility that knowledge of the child's medication status could influence results. Unfortunately, the preparation of placebo tablets was not feasible, given the different medications and dosages used in this study. It would be difficult, however, for the experimenter unwittingly to bias the child's auditory thresholds, because the auditory tasks were computerized, and the experimenter could not hear which stimulus was presented on a given trial.

## ***The Nature of the Effect of Stimulant Medication in ADHD***

There is growing awareness that attention is a multidimensional construct (Mirsky, 1996), and there is controversy over the core underlying deficits in ADHD, which seem to involve an inability to remember and follow through on rules and instructions, to sustain responding

to tasks or other activities, and at the same time to resist distractions (Barkley, 2003). There is debate as to how far inhibition of prepotent responses is a core deficit, and whether such a deficit is influenced by motivational factors (Barkley, 2003). Although our study was not designed to distinguish between theories of ADHD, we argue that the pattern of results provides suggestive evidence in favor of an attentional account because (a) there is a striking difference in performance on the two auditory tasks, (b) poor performance is associated with slowed reaction time, and (c) unmedicated children with ADHD are characterized by greatly increased variability of responding as well as increased thresholds. Let us now consider how this pattern relates to different postulated deficits in ADHD.

First, consider our finding that nonmedicated children with ADHD responded slower as well as less accurately on the FD task. This suggests that impulsivity is not the explanation for poor performance, as that would lead to a speed–error trade-off. Furthermore, purely motivational factors, such as sensitivity to the reward icon presented for successful discrimination of a sound, cannot readily explain the results obtained here, given that the same task format was used in both FM and FD tasks, yet it was only the FD task that revealed deficits in unmedicated children with ADHD.

A similar argument obtains in relation to the idea that auditory discrimination tasks are difficult for children with ADHD because they have deficits in response inhibition (as assessed on the Opposite World and Walk Don't Walk subtests). Some children with ADHD reported verbally that they had not meant to press the response they had made. Previous work by Houghton et al. (1999) showed that children with ADHD had difficulties adjusting subsequent responses despite being given feedback about their performance effectiveness. Although if poor response inhibition were the principal factor leading to erratic performance, we would expect to see deficits on the FM task as well as on the FD task, since the same paradigm was used in both tasks. Instead, deficits were specific to the FD task, with thresholds being both higher and more variable in children with ADHD, reminiscent of results obtained by Sutcliffe and Bishop (2005) in typically developing 6-year-olds.

Another factor that needs to be taken into consideration is fatigue. Children with ADHD are notoriously poor at sustaining interest in repetitive tasks. Breier et al. (2003) proposed that single testing on psychophysical tasks is appropriate as it reduces the possibility of fatigue affecting performance. It was noteworthy in our sample that threshold estimates tended to be stable in typically developing children, but less so in those with ADHD. In our study, unmedicated children with ADHD were particularly likely to show deterioration in thresholds over repeated runs in a session, supporting a fatigue account.

This leaves open the question as to whether increased susceptibility to fatigue is the primary problem or whether children become fatigued because they find the task especially difficult. In this regard, it is of interest to compare the results obtained here with those obtained by Sutcliffe and Bishop (2005) on typically developing children. In that study, we found that 6-year-olds, just like unmedicated children with ADHD, were characterized by performance on the FD task that was considerably more variable than that of older children, both within a run and between runs. We suggested that the difference might reflect problems that some children have in synchronizing their attentional focus with the onset of a critical stimulus. The stimuli in the FM task were longer than the target stimuli in the FD task, so even if the child is not listening at the start of an FM trial, it can be possible to “tune in” and identify the critical stimulus feature. Modifications of the paradigm that cued children in to listen at a particular moment improved FD thresholds in the study by Sutcliffe and Bishop (2005). It would be of interest to use such paradigms with children with ADHD. The evidence from prior studies suggests that this might give more accurate estimates of sensory discrimination, with less contamination by attentional factors. Clearly, further studies varying the stimulus parameters will be needed to test this hypothesis of poor FD performance in children with ADHD, but for the time being we can conclude that poor performance on tasks that involve discrimination of brief auditory stimuli may be due to problems in temporal synchronization of attention, rather than genuine inability to hear differences. This idea ties in with the suggestion by Castellanos and Tannock (2002) that variability of performance in ADHD might be linked to problems in temporal processing. The attention synchronization account that we suggest here is very different in kind from that proposed to account for SLI and dyslexia, where the focus is on inability to discriminate stimuli that are brief or rapid (Tallal, 2000) because of weak temporal resolution of the nervous system.

## Implications for Studies of Auditory Perception in SLI and Dyslexia

In the current study, significant correlations were found between measures of language or literacy and the FD composites when age was controlled, consistent with much previous research. After controlling for the effects of attention with the composite measure of the TEA-Ch subtests, all the significant correlations were removed. It would be rash to conclude that all auditory deficits in SLI and dyslexia are attributable to weak attention, especially since some studies have shown associations in people without attentional deficits (e.g., Breier et al., 2001; McArthur & Bishop, 2004). Our study emphasizes the need to control for attentional factors when conducting

studies in this area, and demonstrates that the impact of attention may be particularly evident in tasks where the child has to focus on a brief stimulus at a particular point in time. Repeated testing of thresholds is often used to get more accurate estimates of threshold, but we found that some children show deterioration of thresholds over prolonged testing sessions. Breier et al. (2003) proposed that single testing on psychophysical tasks is appropriate as it reduces the possibility of fatigue affecting performance. We suggest, however, that instead of recommending the use of a single threshold, it can be useful to obtain repeated estimates, precisely because this can help pinpoint cases where a high threshold may be due to non-sensory factors, rather than to genuine perceptual limitations.

## Acknowledgments

We wish to acknowledge the Experimental Psychology Society and Jesus College, Oxford, for helping to fund this study. We are particular thankful to John West and colleagues at the University of Western Australia for their valuable assistance and guidance. Dorothy V. M. Bishop was supported by a Wellcome Trust Principal Research Fellowship.

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Received July 8, 2005

Revision received October 19, 2005

Accepted January 30, 2006

DOI: 10.1044/1092-4388(2006/076)

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