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Adult Attention-Deficit/Hyperactivity Disorder (ADHD) and the Isolation of Low- and  
High-End Component Operations in Temporal Processing and Time Perception

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### Abstract

Evidence has shown that Attention-Deficit Hyperactivity Disorder (ADHD) is associated with deficits in temporal processing and time perception (Toplak & Tannock, 2004). Current literature, however, focuses on time perception in children with ADHD, while very little research has investigated perceptual deficits in ADHD adults, particularly at stimulus presentation intervals of less than one second. This is significant because, as suggested by Ivry (1996), perception of time intervals of less than one second may involve an internal timing mechanism, while perception of intervals longer than one second involves higher cognitive functioning, such as working memory. In the present study, using a duration discrimination task, we psychophysically examined temporal discrimination characteristics of Control and ADHD-type adults viewing a photopic, foveally-presented circular stimuli presented either steadily or sinusoidally flickered at 15 Hertz for 400 ms or 1600 ms. Using signal detection theory (SDT), differences in accuracy (proportion correct), and its components (i.e., sensory performance ( $d'$ ) and cognitive decision bias based on criterion cut-off ' $c$ ') performance differences between groups were assessed. Efficiency (based on the slopes of the psychometric functions), threshold and the relationship of working memory to temporal processing were measured. Robust transducer function shifts were found across Groups. This combined with our decision bias data, supports the notion of a sensory (versus cognitive/motoric) timing deficit on the part of ADHD-adults compared to Controls. This deficit was particularly apparent in those who showed symptoms consistent with the ADHD-Inattentive subtype. We were also able to demonstrate significant correlations between working memory measures (Wechsler Adult Intelligence Scales – Third Edition) and accuracy, discriminability, and sensitivity (inverse of threshold). We also provided evidence

supporting a two-component system of temporal processing (< 1s and >1s) that relies on either physiological or cognitive (attentional) factors, or both. Flicker had its greatest impact on discrimination from a 1600 standard test interval. While there is less support for the physiological-only structure of the short duration component, much evidence does support the idea of a two-component system with deficient performance by ADHD adults most noticeable for the >1 s component.

## Adult Attention-Deficit/Hyperactivity Disorder (ADHD) and the Isolation of Low- and High-End Component Operations in Temporal Processing and Time Perception

### Introduction

#### Background - ADHD

Attention-Deficit/Hyperactivity Disorder (ADHD) was recognized over 100 years ago, although it was not formally named until 1980, (Eisenberg, 2007; National Institutes of Mental Health (NIMH), 2008). In 1902, George F. Still delivered a series of lectures that were based on his observations of children with disabilities to inhibit their behaviours. Still recognized this inability as not due to intellectual deficiencies nor to environmental influences but rather due to “some morbid condition of the brain” (Still 1902/2006). He further noted that many of the children he observed had noticeable difficulty on tasks that required sustained attention, and that this inattentiveness had a deleterious effect on academic performance. Still went on to describe other characteristics, including antisocial behaviours, on the part of some adolescent subjects. Interestingly, each of the features he described is listed in the Diagnostic and Statistical Manual of Mental Disorders, fourth edition, text revision (*DSM-IV-TR*; American Psychiatric Association (APA), 2000) as symptoms of the now recognized condition “Attention-Deficit/Hyperactivity Disorder (ADHD)”.

The *DSM-IV-TR* (2000) includes ADHD under the section entitled “Disorders Usually First Diagnosed in Infancy, Childhood, or Adolescence”. Although the focus of the current study is on adult sufferers of ADHD, a comprehensive understanding of the disorder necessitates a discussion of the features of the disorder from childhood. This is

especially true given that adult diagnosis of ADHD cannot be made without the presence of childhood symptoms prior to the age of seven.

### **Prevalence**

According to Wender (2000), ADHD is the most common mental disorder in children. In a comprehensive review, Polanczyk, de Lima, Horta, Biederman and Rohde (2007) noted an inconsistent prevalence rate, with some researchers putting the rate anywhere from 1% to 20%. Despite this inconsistency, however, most studies that address the prevalence of ADHD in children suggest a rate of 3% to 5% (NIMH, 2008), while the DSM-TR-IV provides an estimate of 3% to 7% (*DSM-IV-TR*, 2000). Polanczyk et al. (2007) more accurately define the worldwide prevalence of ADHD for individuals under the age of 18 as 5.29%. ADHD in children is more prevalent in males than females at a 9:1 ratio (*DSM-IV-TR*, 2000).

As mentioned above, ADHD can persist into adulthood. It is estimated that 33% to 67% of ADHD children continue to have the disorder as adults. This means that 1% to 5% of the adult population experiences symptoms of ADHD (Wender, 2000). Although many more boys than girls are diagnosed with ADHD, in adults the sex ratio becomes more equivalent. A study by Biederman et al. (2002) compared 140 clinically diagnosed ADHD boys to 140 clinically diagnosed ADHD girls in the domains of social functioning, IQ, achievement and academic difficulties. Their findings showed that compared to the boys, ADHD girls were more likely to be diagnosed as inattentive (vs. hyperactive or combined, see description below), were less likely to have problems in school, and less likely to have comorbid behaviour disorders such as Oppositional Defiant Disorder. According to the authors, the disruptive behaviours of ADHD boys make them more likely to be referred for assessment than girls, resulting in a skewed

ADHD boy to ADHD girl ratio. Biederman and colleagues further suggest that unlike children, adults experience more subtle symptoms of inattention and hyperactivity, and are more likely to refer themselves for treatment of problems when they experience difficulties at work or in the home, unaware that these problems are symptoms of their ADHD. Thus, the diagnostic assessment and treatment for adults with ADHD tend to produce a more equivalent male to female ratio, which may represent a more accurate indicator of gender rates than those observed with children.

### **Symptomology**

According to the *DSM-IV-TR*, a child with ADHD exhibits inattentiveness and hyperactivity more often and more intensely than is expected in non-ADHD children of the same age. Wender (2000) describes a child with ADHD as one who behaves as though he or she is younger than his or her age, requiring repeated simple directives that would be considered appropriate for younger children. Not all ADHD children exhibit both inattentive and hyperactive symptoms, however. An ADHD individual can be classified as: (1) ADHD Combined Type (i.e., six or more *DSM-IV-TR* symptoms of both inattentiveness and hyperactivity present for the last six months, in addition to meeting criteria for age of onset and impairment), (2) ADHD Predominantly Inattentive Type (i.e., six or more *DSM-IV-TR* symptoms of inattentiveness, but not of hyperactivity, present for the last six months, in addition to meeting criteria for age of onset and impairment), or (3) ADHD Predominantly Hyperactive-Impulsive Type (i.e., six or more *DSM-IV-TR* symptoms of hyperactivity, but not of inattentiveness, present for the last six months, in addition to meeting criteria for age of onset and impairment).

Despite all these above-mentioned variants, however, symptoms of hyperactivity, impulsivity and/or inattention are expressed in ADHD children to a degree that is

abnormally high compared to other children. ADHD children may have difficulty with fine motor control, difficulties with balance, and poor hand-eye coordination. Symptoms of inattention in an ADHD child can include the inability to complete a task once started, becoming bored quickly, and being easily distracted by extraneous stimuli. Hyperactive-impulsive-type ADHD children are excessively active, and they do not think of the consequences of their actions. For example, they may fidget, move up and down from their seats and talk incessantly and are unable to inhibit this activity for extended periods. They also have difficulty waiting their turn and interrupt others when talking (*DSM-IV-TR*; NIMH, 2008; Wender, 2000). It is important to note that it is not merely the expression of these symptoms that exclusively characterizes the ADHD disorder, as all children are expected to exhibit these behaviours some of the time. What must be considered in addition to the presence of these relevant symptoms is (1) whether they are experienced more intensely than would normally be expected in children of the same age, (2) whether they persist across more than one situation and context, and (3) whether they cause impairment in an important area of functioning (*DSM-IV-TR*; Wender, 2000).

Although parents and caregivers may notice signs associated with ADHD when a child is a toddler, often the symptoms are not recognized until the child enters primary school. The attentional and behavioural demands of school are at odds with an inattentive and/or hyperactive child's disposition and against that backdrop, the child's symptomology becomes apparent. It is also true that teachers, who are experienced in dealing with many children, are adept at discriminating between those children who behave "normally", and those who experience difficulties in the classroom environment. It is often the teacher who initiates the process of assessment by bringing concerns to the child's parents and consulting qualified professionals at the school (NIMH, 2008).



## Diagnostic Issues, ADHD

In addition to relevant information about ADHD behaviour gathered from medical, academic and family histories of both the child being assessed and his/her parents, a diagnosis of ADHD requires that the individual meet a specified number of ADHD criteria, as listed in the *DSM-IV-TR* (See Appendix A). In reviewing this *DSM-IV-TR* ADHD criteria (e.g., “often has difficulty sustaining attention in tasks or play activities”; “often has difficulty playing...quietly”, *DSM-IV-TR*, p.92) McGough & Barkley (2004) point out that the symptoms described are more applicable to children than to adults. In fact, the use of the current *DSM-IV-TR* definition of ADHD in the diagnosis of the disorder in adults is the subject of much discussion. For example, McGough and Barkley (2004) take issue with the application of ADHD criteria validated on children in the diagnosis of adults. The authors point out that the current *DSM-IV-TR* classification does not reflect the developmental progression of ADHD symptoms. While hyperactivity in children may be manifested as squirming and fidgeting, in adults, hyperactive symptoms are more likely to be expressed as restlessness and irritation. Interrupting others and difficulty in “waiting one’s turn” are symptoms of child impulsivity, while frustration and rash decision-making is a symptom of adult impulsivity. Donnelly, Reimherr & Young (2006) point out that inattentiveness in children includes forgetfulness and susceptibility to distraction, while inattentiveness in adults includes time management difficulties and procrastination. In addition to the apparent incompatibility of child ADHD symptoms and diagnosis of ADHD in adults, McGough and Barkley also question whether the *DSM-IV-TR* requirement for symptoms of the disorder to be present prior to seven years of age is a valid one. They contend that this age limit for ADHD onset is not empirically supported. As a result, many

individuals who likely suffer from ADHD may not be diagnosed because they do not show, or cannot recall, experiencing symptoms before seven years of age. Until research provides valid and reliable criteria for the diagnosis of ADHD in adults, McGough and Barkley recommend the use of scales that have been standardized for adults in the assessment of ADHD, in conjunction with information from significant others. They also suggest that childhood evidence for the disorder is indeed necessary, but that a limit of 12 years of age or the onset of puberty should be the symptomatic requirement.

### **Assessment of ADHD in Adults**

As mentioned above, ADHD is often considered a childhood disorder and this, combined with the different symptom presentations between ADHD children and adults, can make assessment and diagnosis of adults difficult for clinicians (Weiss & Murray, 2003). A typical assessment for adult ADHD involves gathering as much pertinent information as possible about the client and his or her family. Information gathering includes an appraisal of current symptoms, by both the client and someone who knows the client well (e.g. spouse, parent, etc.), followed by an appraisal of childhood symptoms on the part of the client and a parent or caregiver who knew the client as a child. In addition to this information, the clinician obtains medical and psychiatric histories of the client and of his or her family. Information regarding the client's developmental history, from conception to the present day, is also included in the assessment. The clinician is now able to determine if and at what severity the client is experiencing ADHD, and if warranted, provides recommendations to help the client control his or her symptoms.

Information about the past and current symptomology of an adult being assessed for ADHD is usually obtained through self-report and observer-report measures. These scales require that the client rate how often he or she experiences symptoms associated

with ADHD. A person close to the client, such as a spouse, also rates how often the client experiences the symptoms. The same process is followed for children with ADHD. If the child is old enough, he or she completes a self-report form, and a parent or caregiver completes an observer-rating form. If the child is too young to complete the self-report form, a parent or caregiver usually completes the ratings for the child.

The accuracy of self-reports, especially with respect to the recall of childhood symptoms by an ADHD adult, is an issue of concern in recent research literature (McGough & Barkley, 2004; Weiss & Murray, 2003). Research demonstrates, however, that this concern is misplaced. In their study entitled *Use of Self-Ratings in the Assessment of Symptoms of Attention Deficit Hyperactivity Disorder in Adults*, Murphy and Schachar (2000) found significant positive correlations between ADHD subject and observer ratings for both childhood and adult symptoms. This is an important point, as in the present experiment, subjects were asked to report on their past experiences as they relate to ADHD.

### **Quality of Life**

Whether it is labelled or remains undiagnosed, children and adults who suffer from ADHD experience difficulties in many areas of their lives. In her review on the social competence of children with ADHD, Nixon (2001) cites evidence that suggests some of the behaviours exhibited by ADHD children are correlated with peer rejection. For example, “disruptive attempts to enter new groups”; “negative classroom behaviours such as being off-task, noisy or bothersome”, and; “violating the rules” have all been found to contribute to rejection of ADHD children by their peers. In addition, Nixon reports that almost 50% of children with ADHD exhibit aggressive behaviours, with 30% to 50% of ADHD diagnosed children meeting the criteria for Conduct Disorder and Oppositional

Defiant Disorder, both of which include aggressive and hostile behaviour criteria.

Aggression is one of the main reasons children dislike another child and as such, it is not surprising that ADHD children are, in general, less liked than children without the disorder. Unfortunately, non-ADHD children are not alone in their dislike of ADHD boys and girls. Adults also exhibit a negative interpersonal bias towards ADHD children. Teachers have been shown to engage in more negative interactions and are more authoritative with ADHD children. Parents also harbour negative attitudes towards their ADHD children, providing less positive feedback and exhibiting more non-responsive behaviours than parents interacting with their non-ADHD children (e.g., Nixon, 2001).

ADHD children are not oblivious to the social difficulties they face, and research shows they experience feelings of sadness and loneliness as a result. Evidence also suggests that a child's relationships with other children are important with respect to social and emotional competence later in life. Deficits in these areas have been shown to contribute to the occurrence of comorbid psychopathology and a low sense of self-worth later in life, both of which can negatively affect other important areas of life (Wender, 2000).

Substance abuse problems, emotional issues, job-related problems, relational conflict, and legal trouble are experienced by ADHD adults at significantly higher levels than non-ADHD adults (Young, 2000). In her review, Young (2000) reports that ADHD men are twice as likely to be arrested and more likely to be charged with an aggressive offence than non-ADHD adults. Similarly, Mannuzza, Klein, Bessler, Malloy & LaPadula (1998), from a 17 year follow-up of clinically diagnosed ADHD boys, showed that 10% of the ADHD clients experienced non-alcoholic substance abuse problems as adults—a rate that was significantly higher than the non-ADHD control participants, of

whom only 3% experienced non-alcoholic substance abuse problems as adults. In replicating the National Comorbidity Survey, Kessler et al. (2006) determined that ADHD adults experience comorbid psychiatric disorders at significantly higher levels than do non-ADHD adults. For example, in a large sample survey, 38.3% of ADHD respondents met the criteria for mood disorders, compared to 11.1% of the non-ADHD respondents, and 47.1% of ADHD adults experienced anxiety disorders compared to 19.5% of non-ADHD adults. Similar to the results found by Mannuzza et al. (1998), Kessler et al. determined that 15.2% of ADHD adults surveyed met the criteria for a substance use disorder compared to only 5.6% of non-ADHD adult participants. Interestingly, Manuzza et al. (1998) and Kessler et al. (2006) also found that of those ADHD adults receiving treatment, the majority were receiving it for the disorders mentioned above, and not directly for ADHD.

ADHD symptoms in adults are also manifested in the workplace. Kessler, Lane, Stang and Van Brunt (2008) administered surveys to over 4000 workers in a large manufacturing firm. Compared to non-ADHD workers, results indicated lower work performance, more sick days and an increased risk of workplace injury on the part of workers who met criteria for ADHD. In their survey of adults diagnosed with ADHD, Murphy and Barkley (1996) found that ADHD adults moved from job to job more often than the control group. They were also more likely to have been fired, less likely to have finished college, and more likely to have been in fights and suspended from school earlier in their lives. The authors also found that ADHD adults have more difficulty making friends and experience more marital problems than do non-ADHD adults. The relatively high prevalence rates of ADHD in children and adults place a significant burden on health and school systems; on immediate family; and, on the criminal justice system. As

a result, clinicians and researchers consider ADHD to be a serious public health issue (e.g., Polanczyk et al., 2007; Lesesne, Abramowitz, Perou & Brann, 2000).

Considering the aforementioned issues surrounding the diagnosis of ADHD in adults, it is important to note that the presence of adult ADHD was assessed differently in some of the studies presented here. For example, in his follow-up study, Mannuzza et al. (1998) relied on childhood diagnoses. Kessler et al. (2006) conducted a conventional adult ADHD assessment that included self-report of childhood and current symptoms, and the requirement that subjects meet *DSM-IV* criteria for the disorder. In a later study, Kessler et al. (2008) relied on the World Health Organization's Adult ADHD Self-Report Scale to determine the presence of adult ADHD in subjects. Subjects in the study by Murphy and Barkley (1996), however, were diagnosed according to *DSM-III-R* criteria. The lack of consistency in determining the presence of adult ADHD in these studies points to a need for a reliable, stable, and objective method of adult identification. The present study attempts to fulfill this need by non-invasively identifying a reliable biological marker of ADHD, unhampered by symptoms inherent to the disorder.

### **Neurological Correlates of ADHD**

Current research strongly suggests that ADHD is the result of some neurobiological dysfunction, and that this dysfunction is genetically transmitted (NIMH, 2008). "Executive functioning" is a term that appears often in ADHD research and has been defined several different ways including the ability to adhere to a suitable strategy in the attainment of a goal (e.g., Welsh & Pennington, 1988), or the neuropsychological processes associated with self-regulation (e.g., Barkley, 1997). Although these definitions seem to be saying different things, each is referring to a group of abilities associated with frontal lobe function. These abilities include: working memory,

planning, selective attention, sustained attention, verbal ability (e.g. fluency; response inhibition) and processing speed (e.g., Johnson et al., 2001; Lovejoy et al., 1999; Woods, Lovejoy & Ball, 2002). Most of the research that examines the neuropsychological aspects of ADHD reports that adults with ADHD perform more poorly on tests of executive function compared to non-ADHD controls, suggesting some frontal lobe dysfunction on the part of ADHD individuals. Although these studies provide insight into the aetiology of the disorder, which is useful in the diagnosis of ADHD (Lovejoy et al., 1999), understanding ADHD from the perspective of brain functioning requires investigations of neural activity, explicit or implicit, that go beyond the scope of neuropsychological testing. Neurobiological, neurochemical, and neurophysical analyses can assist researchers in assessing the neurological correlates of ADHD at truly meaningful levels; that is, at the level of neurotransmitters and neural pathways. Evidence from these studies can contribute greatly to our understanding of development, progression, and treatment of the disorder, as is demonstrated in the examples below.

Neurochemical research has shown that the neurotransmitters dopamine and norepinephrine play a role in the psychopathology of ADHD. The drugs that are used to treat ADHD act to inhibit re-uptake of these neurotransmitters, suggesting that ADHD may be due to a synaptic cleft deficiency in one or both of them (Pliszka, 2005).

Neuroimaging studies have revealed more specific neuroanatomical correlates of ADHD. According to Valera, Faraone, Murray and Seidman (2007), the posterior inferior cerebellar vermis, the splenium of the corpus callosum, and the right caudate of ADHD individuals show larger volume reductions compared to non-ADHD controls. Through connections with the prefrontal cortex, the cerebellum also plays a role in working memory and attention, although the functional specifics of these connections are

not yet completely understood. Functions such as those described here are all dependent on temporal processing, and this is one of the general overall functions of the cerebellum (Ivry, 1996). Castellanos et al. (1996) used MRI to measure 12 brain regions and their symmetries in 57 ADHD boys and 55 age- and gender-matched non-ADHD controls, all between the ages of 5 to 18 years. The authors found that the ADHD boys and girls had an overall smaller cerebral volume and smaller cerebellums than non-ADHD controls. Other studies have also reported anatomical cerebellar abnormalities and some decreased neural activation in the cerebellum in individuals with ADHD, however these deficiencies do not address specific cerebellar functional deficits (e.g. Castellanos et al., 1996; Castellanos et al., 2001; Mulder et al., 2008).

Using fMRI techniques, Valera, Faraone, Biederman, Poldrack and Seidman (2005) examined the brain activity of ADHD adults, aged 18 to 55 years, who were engaged in a working memory task. The presence of ADHD was determined using a *DSM-IV* ADHD telephone questionnaire, followed up by a *DSM-IV* ADHD structured interview. Control subjects also completed the telephone questionnaire and interview and were included if they were classified as not having ADHD or other disorders. Magnetic resonance scanning was done during a working memory task in which subjects were required to view a series of letters and press one of two buttons in response to target or non-target stimuli. The target was any letter that was the same as the one that preceded it two trials prior to presentation of the target stimulus. Non-targets were dissimilar letters. Although there were no performance differences between ADHD adults and controls on the working memory task, the authors did find significant decreases in fMRI-image defined cerebellar brain activity during task performance in the ADHD adults.



In the present study, we used a psychophysical temporal discrimination task that required immediate interval duration judgments and used our neurometric findings to assess potentially aberrant neurological pathways associated with both ADHD and temporal processing.

### **Temporal Processing**

Pathways and dedicated sensory receptors have been described for hearing, vision, taste, touch, and olfaction. None, however, has been clearly identified for our sense of time. In spite of this, we are able to perceive time, whether conscious of it or not, in increments that range from milliseconds to years.

The inability to identify a clear structure or pathway should not be taken to mean that researchers have not attempted to locate the area(s) responsible for temporal processing. In fact, psychophysical studies have demonstrated that several areas within the brain are implicated in temporal processing. Some of these areas include the cerebellum, the basal ganglia, the prefrontal, premotor and supplementary cortices (e.g., Ivry & Spencer, 2004; Mangels, Ivry & Shimizu, 1997). What is not known is whether or not the activity of these areas is controlled by a “master timing clock”. It has been proposed that different neural pathways operate independently depending on the type of timing task or situation an individual encounters (e.g. Ivry, 1996). This question is, in fact, a central theme in research of temporal processing. Unfortunately, there are no generally accepted definitions for many of the terms used by researchers in this area, and as such, it becomes necessary to first determine how researchers define terms such as “time perception”, “time estimation” and “time judgment”. According Toplack and Tannok (2005) and Radonovich and Mostofsky (2004), the phrase “time perception” refers to the perceived length of a time interval. This differs from Rammsayer’s (2002)

definition of time perception as the processing of temporal information in the range of milliseconds. The phrase “time estimation” is equally ill-defined. According to Rammsayer, the processing of temporal information in the range of seconds is time estimation or temporal generalization, while Barkley, Murphy and Bush (2001) consider time estimation to be the judgment of the length of time intervals, irrespective of duration. The confusion that results from this lack of a generally accepted terminology is evident when one attempts to conduct a literature review on the subject. For example, in their study on time perception, Toplack and Tannock used a duration discrimination task which required subjects to discriminate between two time intervals. Subjects heard two sets of tones (or saw two sets of images) separated by a short duration gap. Subjects had to decide which of the two presented stimulus epochs was longer. This task was performed with both a short, 200-ms and a longer 1000-ms standard interval. Rammsayer and Brandler (2004) performed a similar experiment; however, they used a task that required subjects to judge the length of a presented stimulus intervals. A task that required subjects to discriminate intervals less than one second in duration was referred to as “duration discrimination”, while judgment of intervals greater than one second was referred to as “temporal generalization”. In order to decipher and compare findings of these studies, one must first determine how each group of researchers chose to define the same processes. In the following sections, relevant terms will be clearly defined, and the explanation of methodologies when the terms are used will be provided.

For our purposes, temporal processing of intervals less than one second in length will be referred to as “low-end temporal processing” or “low-end temporal operations”, while “high-end temporal processing” or “high-end temporal operations” will be used for

intervals greater than one second. An explanation for this terminology is provided in the sections below.

With respect to the neurological correlates of how and where temporal processing occurs, researchers have hypothesized that (1) there is one specialized area (i.e. one internal clock) that regulates timing, or (2) that task-specific timing mechanisms are distributed throughout different areas of the brain (Rammsayer & Brandler, 2004; Ivry, 1996). To test these hypotheses, Rammsayer and Brandler (2004) conducted a psychophysical study to determine if five basic timing tasks were associated with different temporal processing mechanisms. The different tasks included duration discrimination, simultaneity and successive tasks, a generalization task, a rhythm perception task, and a temporal order judgment task. The duration discrimination task involved the random presentation of a standard interval and a comparison interval (both  $<1$  s), separated by a 900 ms gap. The subject was required to state which interval was longer. A just noticeable difference (jnd) was used to measure performance. The simultaneity and successiveness tasks involved presentation of two noise bursts separated by time intervals ranging from 1 to 40 ms. The subject had to decide if the two separate tones were perceived separately (successiveness), or as one tone (simultaneity). A measure of 75% correct was used to assess performance threshold. The temporal generalization task differed from the duration discrimination task in that it relied on long term memory. A reference duration ( $>1$  s) was presented in Phase 1 of the experiment, and subjects had to judge whether durations presented in Phase 2 were the same as the reference duration presented in Phase 1. Performance was determined by comparing the proportion of hits (correctly identifying equal intervals) to misses (incorrectly identifying non-equal intervals as the same duration). The rhythm perception task involved the

identification of a temporal deviation from a pattern of clicks devoid of any characteristics that might affect the perception of rhythm. In this task, rhythmic patterns of six successive millisecond clicks were presented through headphones. Subjects had to decide whether the rhythmic pattern was regular (i.e., all patterns were of the same duration), or irregular (i.e., one pattern seemed different in duration from the others). The 75% correct measure was determined for each participant in this task as well. Finally, a temporal order judgement task was used to determine the amount of time required between the onsets of two stimuli in order for them to be accurately perceived. This task included visual and auditory stimuli, and it proceeded in two series, each comprised of 32 trials. In the first series, a tone was presented 200 ms after presentation of a light stimulus, while in the second, the light followed the tone by 200 ms. The subject had to indicate whether onset of the tone or of the light occurred first. The 75% correct threshold was determined for each participant. The mean thresholds for each task were determined and their correlation assessed.

The highest task threshold correlations were found between the duration discrimination, temporal generalization and temporal order judgment tasks, while only marginal correlations were found between these and the rhythm perception and simultaneity and successiveness task.

According to Rammsayer and Brandler, these findings suggest that rhythm perception and simultaneity and successiveness are not functionally related to interval timing. The authors also suggested that the correlations found between duration discrimination, temporal generalization and temporal order judgment tasks point to a shared interval-timing mechanism necessary to discern properties of time intervals in a given temporal context.

### **Duration Discrimination and Temporal Information Processing (TIP)**

The temporal information-processing (TIP) model is used to describe interval timing and duration discrimination. This model hypothesizes that time judgement involves an internal clock, referred to as a “pacemaker”, a switch, and an accumulator. Upon presentation of a temporal stimulus, the pacemaker generates pulses relative to the individual’s level of arousal, defined as one’s normal state of wakefulness, or as a state of physiological excitement that results from exposure to some stimulus. The accumulator “collects” these pulses when the switch is closed and acts as a counter. The number of pulses the accumulator has collected during the closing of the switch represents the stimulus duration, or time interval to be judged. Thus, when a critical stimulus is presented, the switch closes, allowing the pulses to be sent to the accumulator. This marks the start of the duration to be perceived. Opening of the switch occurs when the interval has ended, usually delineated by the offset of a critical stimulus. This model also involves working memory (i.e., the ability to store information for immediate use in processes such as problem-solving and decision-making) and reference memory. The idea, here, is that information from the activated accumulator is stored in working memory, and a replica is stored in reference memory. When it is time to make a perceptual decision regarding interval duration, the information in working memory is compared to that stored in the reference memory. Although it has been criticized, the TIP model is the most widely used model in research on temporal processing (e.g., Droit-Volet, Meck & Penney, 2007, Rammsayer & Brandler, 2004; Lejeune, 1998).

As noted earlier, Rammsayer and Brandler (2004) suggest that duration discrimination and interval timing share a common mechanism, which they contend, supports the TIP model. According to the authors, duration discrimination involves two

types of intervals: a “filled” interval in which some stimulus (e.g. a tone or a flash of light) is presented, and an “empty” interval in which no stimulus is presented. The beginning and end of the filled interval are marked by stimuli presentations and presentation completions, while the beginning and end of the empty intervals are marked by no stimuli – it is simply a silent or blank interval. Interval timing has been shown to be affected by the nature of the stimulus; for example, visual presentations are often perceived as shorter than auditory presentations in duration judgements (e.g., Penney, Gibbon & Meck, 2000). This has raised questions as to whether aspects other than sensory modality could also affect perception of time intervals. In particular, it has been suggested that filled and empty temporal intervals may be processed differently. Rammsayer and Brandler (2004) indicate that for their short auditory time intervals, the filled intervals (~50 ms) are better judged than empty intervals (~900 ms). The authors further describe one approach that can be applied to determine if two timing tasks depend on a single mechanism. According to Rammsayer and Brandler, if the same timing mechanism underlies two different timing tasks (e.g. duration discrimination and temporal order judgment, described above), then the timing variability of the tasks should be highly correlated. With respect to the TIP model, the temporal stimulus in the definition above is a sensory cue (e.g. light, sound) that fills the interval, or its absence in the case of an empty interval, while the ensuing arousal is represented as the number of pulses emitted from the pacemaker. The filled intervals represent more salient stimulus presentations, and elicit more pulses than the empty intervals which, according to the authors, could result in more accurate time judgments as defined by lower duration difference thresholds in an interval discrimination task.

Some investigators have tried to demonstrate the existence of an internal clock by either speeding up or slowing down the pacemaker. This entrainment of pacemaker speed was investigated by Droit-Volet and Wearden (2002), who examined the effect of visual flicker on duration discrimination in three groups of children. The children were divided into three groups based on age (three years, five years and, eight years), and each child participated in two experimental conditions. During the first condition, a “white” circle was presented on a computer screen for five seconds, and then a circular target “blue” stimulus was presented on the screen for either 200 ms (short, S) or 800 ms (long, L) durations. After an inter-stimulus interval of one, two, or three seconds, a comparison stimulus, identical to the “blue” target stimulus in all ways but for its duration, was presented. By pressing a key denoted either as ‘S’, for the short interval, or as ‘L’ for the long interval, subjects were required to indicate if the comparison stimulus interval was shorter or longer than the target interval. Fourteen trials were conducted. For seven of them, the white circle was flickering, for the other seven it was not. Children were told not to pay attention to the flickering, but to look at the white and blue circles carefully. The second condition was identical to the first except the short ‘S’ duration was lengthened to 400 ms, and the long ‘L’ duration to 1600 ms. They found that the flicker affected subjective time, causing the subjects to perceive the longer interval as more similar to the shorter standard interval duration. As an explanation, the authors suggested that the flickering manipulation caused changes in subjective time by increasing pacemaker speed, thereby shortening perceived durations.

Recently, Wesner and Prenger (2005) examined the possible influence of frequency entrainment on low-end adult pacemaker operations in a timing sensitivity task. Steady-state or sinusoidally-flickering visual stimuli were presented during two

intervals in which the standard durations were either 400 ms or 1600 ms and the comparison stimuli were either the same or longer than the standard. The task was for the subjects to determine which of the randomly presented two intervals was of greater duration. When the visual stimulus was flickering, the timing sensitivity for the longer duration improved. Wesner and Prenger suggested that increasing the pacemaker speed may have had the effect of increasing timing resolution, accounting for the improved sensitivity for the 1600-ms standard duration. Why this was not the case for the shorter 400-ms standards was not clear, although it was suggested that the durations were too short for proper trial isolation ending up with possible trial combinations with adjacent presentations.

### **Attentional Gate Model (AGM)**

Although the TIP model provides a working hypothesis of temporal processing, it has been criticized for not taking into consideration the cognitive components of time judgments. An example of this can be found in the manner in which interval timing is judged (i.e., prospective or retrospective judgments). A prospective judgment is one that is made when the subject is informed, prior to making a duration estimation, that such an estimation is expected. A retrospective judgement is one that is made without prior notice (i.e., the subject is not aware that he or she will have to make a duration estimate). According to Zakay and Block (1996), prospective judgments are directly related to the amount of attention the subject pays to the temporal qualities of the stimulus, whereas retrospective judgements are related to information stored in memory. The authors contend that the TIP model does not take into consideration the influence attention has on the temporal elements of stimuli presented in prospective duration judgement tasks. To address this issue, Zakay and Block proposed the Attentional Gate Model (AGM) of



temporal processing. In this model, a “gate” is added to the TIP model, between the pacemaker and the switch. Opening of the gate is influenced by the amount of attention that is dedicated to the temporal characteristics of a stimulus presentation during a prospective duration judgement. The more attention allocated, the more widely the gate is opened and the more pulses or “temporal information” can pass to the accumulator, referred to in the AGM model as the “cognitive counter”.

Simply put, TIP models the processing of temporal bits of stimulus information without factoring in the attentional resources that may be allocated, while the AGM incorporates these top-down influences. Both the TIP and Attentional Gate Models of temporal processing are based on the notion of a specialized internal clock that is ultimately responsible for the psychological representation of time.

### **Low- and High-End Component Operations in Temporal Processing**

Some research on temporal mechanisms provides evidence for two distinct systems. One is a low-end component system for processing of intervals less than one second, where “low-end” refers to temporal processing outside of conscious control, unaffected by cognition or attention. The other is a high-end component system for processing of intervals greater than one second, where high-end refers to processes mediated and modulated by cognitive factors such as working memory and attention. Findings in support of a two-component operating system that flanks the one second duration is provided below.

Lewis and Miall (2003) used fMRI to measure brain activity of five right-handed males and three right-handed females (mean age = 26) while they performed temporal judgment tasks for intervals of less than one second (0.6 s) and greater than one second (3 s). The authors hypothesized that cortical motor systems and the cerebellum are active

during judgment of the shorter interval, while prefrontal and parietal cortices are active during judgment of the longer interval. A white line was projected onto a screen that could be viewed inside the fMRI device. Subjects were asked to judge either the duration of presentation of the line, or the physical length of the line, against a standard presentation of a line of fixed length for durations of either 0.6 seconds or 3 seconds. According to the authors, fluctuation and judgment of the length of the line served to ensure sustained attention throughout the experiment. Comparison time intervals were randomly chosen, while length of the line increased or decreased by a random fraction, always within 20% of the standard length. From a whole brain scan, Lewis and Miall determined that while some areas (e.g. insula, dorsal prefrontal cortex, right hemisphere pre-supplemental motor area) were active during the assessment of both the 0.6 s and 3 s intervals, the cerebellum was active only during the assessment of the shorter 0.6 s interval. The left hemisphere inferior parietal cortex, associated with attention, and the posterior cingulate cortex, associated with memory, were active only during assessment of the longer 3 s interval. Not only do these findings provide evidence for two timing systems, one for millisecond timing and one for timing in the range of seconds, but also these findings demonstrate that the cerebellum is implicated in temporal processing at time intervals of less than one second, while areas such as the left inferior parietal cortex and the posterior cingulate cortex are associated with processing at intervals greater than one second.

Wesner and Prenger (2005) provided further evidence in support of two separate systems for processing temporal information above and below the 1000 ms mark. As described earlier, subjects were required to discriminate between two time intervals using either a 400- or 1600-ms standard. The visual stimulus was either sinusoidally flickered

or not. Results demonstrated increased performance (i.e., decrease in duration errors), for the flicker-1600-ms standard intervals, and decreased performance for the flicker 400-ms standard intervals. The same relationship was observed in the no-flicker condition, however, the lowest thresholds were observed in the 1600-ms flicker condition. The authors suggested that some cognitive strategy (e.g., counting) aided by the entraining stimulus may have been applied for the longer interval, while no such strategy was available or possible to subjects during the shorter interval presentations.

Rammsayer and Lima (1991) hypothesized that performance on a one second standard-interval duration discrimination task could be affected by a high cognitive load demand due to interference. For example, in their experiment, a cognitive load was the learning of a visually presented word 1500 ms prior to a duration discrimination task. Rammsayer and Lima hypothesized that performance of the task under such a high cognitive load would not be affected during a duration discrimination task of 50 ms, because such a task required only low-end operations. To test these hypotheses, Rammsayer and Lima performed two experiments: one aimed at targeting low-end timing operations, the other high-end timing operations. In both experiments, subjects performed an auditory duration discrimination task under either high or low cognitive load. In the low-end, low cognitive load condition, presentation of a computer-generated 50 ms standard interval was followed by a 900 ms inter-stimulus interval. A comparison interval was then presented. The experiment included 50 standard interval, interstimulus interval, comparison interval trials. The comparison interval varied according to subject performance, and duration was increased by eight ms on each of the first ten trials, by four ms on trials 11-30, and by two ms on trials 31-50. For each trial, subjects had to decide which of the intervals was longer by pressing a key marked either “first interval

longer” or “second interval longer”. For the low end, high cognitive load condition, the discrimination task was the same as just described, however subjects had the additional task of memorizing a word for a later recall test. The word was presented for 1500 ms, and following a 900 ms inter-stimulus interval, the duration discrimination task was carried out. Rammsayer and Lima found no significant effect of cognitive load on duration discrimination for these low-end 50-ms standard duration tasks. These findings indicated that the word memorization task did not interfere with the short duration discriminations. The design of the high-end operations experiment mimicked that of the low-end processing experiment, however the standard interval in the duration discrimination task was 1000 ms, and the first comparison interval was 2000 ms. The duration of the comparison interval changed by 200 ms for each of the first ten trials, by 100 ms for trials 11-30, and by 50 ms for trials 31-50. As in the first experiment, subjects in the low cognitive load condition completed the duration discrimination task without any memory task, while those in the high cognitive load condition were required to memorize a word immediately prior to completing the duration discrimination task. Results in this case demonstrated that duration discrimination was significantly better in the low cognitive load group, indicating that duration discrimination of intervals greater than one second are mediated by some cognitive processes which can be interfered with by other cognitive tasks such as word memorization.

The Rammsayer and Lima findings suggest that duration discrimination at intervals equal to one second are cognitively mediated and thus influenced by cognitive load, while discrimination of intervals less than one second are low-end operations that are immune to cognitive load interference. Such a finding supports the two-system temporal processing mechanism: intervals greater than one second are influenced by

cognitive factors and intervals less than one second are influenced by low-end timing elements—possibly by such mechanisms as a low-end pacemaker or oscillator (e.g., suprachiasmatic nuclei).

Considering both the cognitive (e.g. Woods, Lovejoy & Ball, 2002), and temporal processing deficits (see section ADHD and Temporal Processing below) associated with adult ADHD, we expect ADHD subjects to perform worse than non-ADHD controls on duration discrimination tasks for intervals both longer *and* shorter than one second, the former being based on deficit findings with short interval tasks in ADHD children (Toplack & Tannock, 2005). Note that a finding of ADHD adults performing more poorly on duration judgment tasks greater than one second is not as informative with respect to understanding the neurological underpinnings of a performance decrement for trials less than one second. This is because the shorter durations are likely only influenced by low-end temporal processing operators that do not involve the potential high-end cognitive confounds. In other words, poor performance on a longer duration discrimination task demonstrates what researchers already know: ADHD adults have problems with executive functioning. Poor performance on shorter discrimination tasks, however, provides clearer evidence of potential aberrant pathways associated with ADHD that are not obscured by possible non-temporal-based cognitive deficiencies.

### **Individual and Group Differences in Timing Sensitivity**

Research clearly demonstrates that temporal processes differ according to certain group and individual characteristics. For example, Rammsayer (2002) examined the effect of personality dimensions, as measured by Eysenck's Personality Questionnaire-Revised, on judgement of time duration compared to standard intervals of 50 ms and 1000 ms. He found that with the 1000 ms trials, those who scored high on the dimension

of psychoticism had lower difference thresholds than did those who scored low on psychoticism.

Tipples (2008) examined the influence of negative emotionality, as measured by the EAS Temperament Survey for Adults, on the effects of facial expression on duration judgments. Visually-presented stimuli were facial images of anger, fear, happiness and neutral expressions. In the first trial, an angry expression was presented for a 400-ms standard duration, and an angry expression stimulus was presented for comparison intervals of 600 ms, 800 ms, 1000 ms, and 1200 ms. This was repeated for all the remaining facial expressions, and all emotional expressions were presented again for a 1600-ms standard interval. Subjects ranging in age from 18 to 35 years were required to indicate, by pressing one of two keys, whether the comparison interval was longer or shorter than the standard interval. Results showed that as negative emotionality increased, so did subjective duration. That is, differences in perceived temperament correlated with differences in the subjective perception and estimation of time. The findings by Rammsayer (2002) and Tipples (2008) both demonstrate that an individual's personal and perceived emotional environment can interact with his or her time sensitivity.

Use of pharmaceuticals can also influence individual differences in temporal processing. In a study entitled *Neuropharmacological Evidence for Different Timing Mechanisms in Humans*, Rammsayer (1999) investigated the orally administered effects of Haloperidol (dopamine antagonist), another dopamine (DA) antagonist Midazolam—a benzodiazepine that acts as a sedative, impairs memory function, and acts to inhibit release of dopamine into the synaptic cleft—and the cholinergic receptor antagonist Scopolamine, on short duration (50 ms) and long duration (1000 ms) time perception.

Eighty human males ranging in age from 20 – 35 years served as subjects. Results showed that for the short time interval tasks, only the Haloperidol significantly reduced performance, compared to a placebo and the Midazolam group. There was no significant difference in short interval performance between the Midazolam group and the Scopolamine group, nor did the Midazolam and the Haloperidol groups differ significantly from each other. No explanation is provided as to why the Midazolam did not result in a significant reduction in performance. Performance for the long interval task was also significantly reduced by the Haloperidol and by Midazolam. This finding is particularly interesting in the context of the present study because the activity of the Haloperidol putatively produced neurological influences similar to what is postulated to be occurring naturally in the brains of ADHD individuals. For example, in his review of the neuropharmacology of ADHD, Pliszka (2005) cites evidence of reduced CFS levels of homovanillic acid (HVA, a metabolite of dopamine) in ADHD individuals compared to non-ADHD individuals. According to the author, these lower DA levels may be the result of activity at (1) the enzymatic, metabolic level where tyrosine hydroxylase activity is inhibited, (2) the dopamine transporter where reuptake is enhanced thereby reducing DA synaptic cleft levels, or (3) the receptor level where postsynaptic DA receptors are inhibited.

Some mental disorders have been shown to affect an individual's experience of time. Elvevag, McCormack, Gilbert, Brown, Weinberger and Goldberg (2003) investigated time perception in schizophrenic patients and reported a time perception deficit for schizophrenic subjects, as defined by greater just noticeable differences in a duration discrimination task for time intervals below 1000 ms. Considering the research presented above, one could argue this finding is suggestive of a low-end temporal

processing deficit that is not mediated by cognitive or attentional processes on the part of schizophrenic participants.

Given these individual and group differences in temporal processing, it is not surprising that research has also shown ADHD to significantly influence temporal information processing.

### **ADHD and Temporal Processing**

The following discussion focuses on the temporal processes of individuals who suffer from ADHD. Fortunately, the issue has been widely researched in ADHD children; unfortunately, very little research has focused on adults with ADHD.

Smith et al. (2002) conducted a study to examine temporal discrimination in children with and without ADHD. For the task, two circles were presented, one for 1000 ms and the other for 1300 ms. Subjects were then asked to identify which of the stimuli was longer in duration. A staircase procedure was used. If a subject made a mistake, the differences between the durations to be compared increased by 15 ms, while the difference between durations decreased by 15 ms for correct answers. Results showed that ADHD children had lower timing sensitivity as demonstrated by higher jnd thresholds than controls. While non-ADHD control subjects were able to discriminate intervals that differed by 190 ms, the ADHD group required difference intervals of at least 240 ms.

Using psychophysical temporal discrimination tasks, Toplack and Tannock (2005) examined time perception in ADHD adolescents. They also assessed memory, intelligence and reading ability. The temporal discrimination tasks involved discriminating durations delineated by both visual and aural stimuli. Standard time intervals were either 200 or 1000 ms. For the 200-ms standard “short” duration, intervals



changed by 5 ms, beginning at 230 ms, while intervals for the 1000-ms standard “long” duration changed by 25 ms increments, beginning at 1200 ms. The authors found that ADHD subjects performed significantly poorer than non-ADHD controls on short and long duration conditions for all visual and auditory discrimination tasks. Results also demonstrated a greater number of significant correlations between memory, assessed using standardized assessment tools, including the Wechsler Abbreviated Scale of Measurement (WASI) and discrimination thresholds for the 1000 ms standards. Memory performance and discrimination thresholds for the shorter 200 ms standard duration did not show significant correlations. No significant correlations were found between performance of ADHD or Control subjects and reading ability or intelligence.

Toplack’s and Tannock’s findings demonstrated a time deficit on the part of ADHD adolescents for both their “short” and “long” durations. Correlational results also partially supported previous research (see Rammsayer & Lima, 1991) that implicated memory in the discrimination of intervals greater than one second in duration but not for the short interval discrimination task.

In a rare study on time perception in ADHD *adults*, Barkley, Murphy and Bush (2001) compared the performance of ADHD and non-ADHD adults (17 to 28 years) on time estimation and time reproduction tasks. For the time estimation task, participants were required to verbally state how long a duration interval lasted. Subjects had to verbally estimate time durations of 2, 4, 12, 15, 45 and 60 seconds. An examiner held a stop watch and indicated the beginning and end of each time interval. At the end of the interval, subjects were instructed to tell the examiner how long the interval lasted. For the reproduction task, time intervals were visually presented (e.g., the duration interval between a light going on, then off) and the subject was required to replicate the time

interval. The examiner presented sample intervals (the same intervals used in the time estimation task) and the subjects had to reproduce the interval by telling the examiner when to start and stop the stopwatch. The authors also assessed comorbidity of oppositional defiant disorder (ODD), conduct disorder (CD) depression, and anxiety with ADHD as well as comparing the time measurements without a comorbid specifier. No significant differences between groups were found in the time estimation task. For the time reproduction task, however, all ADHD subjects provided significantly shorter reproductions than the non-ADHD controls. Overall, comorbid disorders were not found to have any significant effects on time estimation or reproduction. Similar to Toplack and Tannock's (2005) conclusions, Barkley et al. suggested that the reproduction task differences demonstrated working memory deficits on the part of ADHD subjects. The authors contend that the ability to keep the presented time interval in mind is deficient in ADHD adults, implying working memory impairment.

Each of the above studies contributes to the body of research that shows ADHD to be associated with some deficit(s) in temporal processing. These deficits have been demonstrated for both high-end and low-end temporal operations in ADHD children and in high-end operations for adults. As research demonstrates, the estimation of intervals greater than one second involve the application of cognitive strategies such as working memory and attention. In the case of ADHD, deficits in tasks that invoke high-end temporal processing, whether it be attention or memory systems, is to be expected. This is true especially given the apparent consensus on the part of clinicians and researchers that ADHD is a disorder of attention and working memory. Perception of intervals of less than one second, however, is outside of cognitive control and may be vulnerable even in ADHD adults who may not be able to cognitively compensate for a deficient low-

end temporal processing circuitry. Detection of a low-end temporal processing deficit in adult ADHD would be more than a description of a behavioural manifestation of the disorder, it would be a step towards better understanding the underlying mechanisms by which the disorder occurs and persists, which may lead to improved diagnostic protocols and treatment.

### **The Present Study**

The present study was designed to add to the collective understanding of adult ADHD by examining whether ADHD high-end deficits persist in adulthood, and more importantly, to objectively and noninvasively measure possible changes in the low- and high-end components of temporal processing. We believed that our findings would contribute to a greater understanding of the potential pathological pathways associated with afferent performance and cognitive strategizing in adult ADHD.

We hypothesized that, compared to non-ADHD controls, ADHD adults would exhibit more time perception performance deficits at intervals of greater than one second. As noted above, temporal processing deficits for high-end temporal operations have been consistently found in ADHD children, and in at least one study, in adults.

Research on low-end temporal operations has focused only on ADHD children (Toplack & Tannock, 2005), and findings indicate potential dysregulation. We also assessed temporal processing and time perception in ADHD adults at intervals of less than one second, enhancing our understanding of a possible two-component temporal processing system and the potential deleterious consequences of ADHD on such a system.

In keeping with the two-component idea of temporal processing, we also hypothesized that increasing low-end pacemaker speed through flicker entrainment

would have differential effects on time interval judgements in adults with and without ADHD. Findings from Wesner and Prenger (2005) indicate that increasing pacemaker speed through putative entrainment stimuli can improve timing sensitivity for intervals longer than one second. Preceding the duration judgement task with a repetitive flicker (15 Hz) was found to increase judgment accuracy for a 1600-ms standard time interval. This effect was most pronounced for low-sensitivity timers. Low- and high- sensitivity timers were identified based on the median average threshold for both durations and flicker/no flicker conditions. Those whose thresholds were above the mean were categorized as low-sensitivity timers, while those whose thresholds were below the mean were categorized as high-sensitivity timers. In the present study, we anticipated ADHD adults to be “low-sensitivity timers” given research that suggests ADHD individuals have higher thresholds than do non-ADHD individuals (e.g., Smith et al., 2002; Toplack and Tannock, 2005). Considering the findings by Wesner and Prenger (2005) presented above, one would expect that increasing pacemaker speed through stimulus entrainment will result in relatively improved timing sensitivity in ADHD adults compared to little or no change in non-ADHD controls.

We further hypothesized that poorer performance on working memory tasks from the Wechsler Memory Scales (See Methodology) would correlate with temporal sensitivity decrements for high-end temporal operations (i.e., long duration judgements) in ADHD adults, while no such relationship would exist with low-end temporal operations (i.e., short duration judgments). As temporal processing of intervals less than one second in duration is considered to be outside of cognitive, or conscious, control we expected no effect of working memory on duration judgements of intervals less than one second (e.g., Ivry, 1996; Rammsayer, 1999, 2004). Although a finding of ADHD

performance decrements for low-end temporal processing was not expected, such a result would provide an even broader picture of the deleterious consequences of ADHD beyond simply a dysfunctional top-down mechanism.

### Method

This method was adapted from the recent dissertation entitled: *Individual differences in timing sensitivity: Implications for interval timing model* (Prenger, 2005).

#### Participants

Participants included 32 adults (males,  $n = 11$ ; females,  $n = 21$ ) recruited from the Lakehead University student population; ages ranged from 18 – 39 years ( $M = 22.4$ ;  $SD = 4.5$ ) (See Appendix B for additional demographic information). For their participation, three bonus marks were added to each undergraduate's Introductory Psychology final grade and graduate participants were entered into a draw for \$50. Participants were divided into two groups: non-ADHD controls, and ADHD-Total. The ADHD-Total group was further broken down into two subgroups: ADHD-other and Inattentive. The ADHD-other group was made up of those participants who had ADHD symptoms consistent with the ADHD Predominantly Hyperactive-Impulsive Type or ADHD Predominantly Combined Type. Those in the Inattentive group exhibited symptoms reflective of the ADHD Predominantly Inattentive-type. Every participant completed the Conner's Adult ADHD Rating Scale (CAARS) - Long Version. A registered clinical psychologist with extensive knowledge and experience in the assessment and identification of ADHD symptoms reviewed each CAARS profile. Participants identified as being ADHD-type (i.e., exhibiting ADHD symptoms to a clinically significant degree, equivalent to a  $t$ -score of greater than 65 on the CARRS scales) were included in the

Adult ADHD group (See Assessment Measures below). Working memory was assessed using two subtests from the Wechsler Adult Intelligence Scales – Third Edition (WAIS-III) (Wechsler, 1997). Participants were asked to provide demographic information, including age and gender. Each participant's visual colour blindness and visual acuity were assessed.

### **Assessment Measures**

The CAARS – Long Version consists of 66 items that make up nine subscales. These subscales include: Inattention/Memory Problems; Hyperactivity/Restlessness; Impulsivity/Emotional Lability; Problems with Self-Concept; Inattentive Symptoms; Hyperactive-Impulsive; Total ADHD Symptoms; and ADHD Index. The measure also includes an Inconsistency Index. The ADHD Index subscale includes the items that best distinguish ADHD adults from non-ADHD adults. The Long Version takes approximately 30 minutes to complete. Examinees are required to rate items related to their behaviours or issues on a 4-point scale, where 0 = Not at all, 1 = Just a little, 2 = Pretty much, Often and, 3 = Very much, Very often (Conners, Erhardt and Sparrow, 1999). Internal reliability refers to the degree to which all items on a subscale measure the same construct. For 18 to 39 year old males and females, internal reliabilities for the CAARS Self-Report -Long Version subscales range from 0.64 to 0.91. Test-retest reliability refers to the stability of the subscales over time, determined based on a correlation between an individual's scores from two separate test administrations. Test-retest reliabilities for the CAARS Self-Report -Long Version subscales range from 0.80 to 0.90. Discriminant validity refers to the ability of a test to distinguish between groups. The CAARS-Long Version was given to a group of adults diagnosed with ADHD and to

a group of adults not diagnosed with ADHD. Results for each group were compared and the CAARS- Long Version was found to correctly classify groups 85% of the time.

To determine the degree to which working memory relates to time sensitivity and perception in ADHD adults, we administered the Digit Span Forward and Backward and the Letter-Number Sequencing subtests from the Wechsler Adult Intelligence Scales – Third Edition (WAIS-III) (Wechsler, 1997). The Digit Span Forward task requires that the experimenter read aloud a series of numbers to the participant, who must then recall them out loud in the order they were presented. The series increase in length as the task progresses. The Digit Span Backward task is different from the Digit Span Forward Task only in that the participant must repeat the sequence back in reverse order. In the Letter-Number Sequencing subtest, the experimenter must read aloud a combination of letters and numbers. The participant must repeat the combination, leading with the numbers in numerical order followed by the letters in alphabetical order. There are a total of seven items, each consisting of three trials made up of different combinations of letters and numbers.

The Ishihara plate test for colour blindness (1993, 24-plate edition) and the Freiberg near visual acuity test (Bach, 1996) were administered to all participants to ensure normal or corrected-to-normal vision. Participants were excluded if they had vision problems and/or were colour-blind.

### **Psychophysics Apparatus & Visual Stimuli**

Tasks were conducted in a darkened area to prevent any interference by ambient light. Stimuli were presented in the center of a high resolution Nanao video monitor (13° X 16°) at a screen distance of 75 cm from the participants' entrance pupils.

Stimuli were designed using VisionWorks™ software. Participants indicated if a visual test interval was the same or longer than a standard interval by pressing a right (“longer than”) or left (“same as”) key on a response pad.

It is generally known that visual resolution and acuity is greatest in the fovea, and that discrimination of small changes in time is significantly better when the event stimuli are foveally presented (McKee & Taylor, 1984). Research has also demonstrated that the short-wavelength sensitive (SWS) cones have a response latency that is 20 to 30 ms longer than that of the middle- (MWS) and long-wavelength sensitive (LWS) cones (Smithson & Mollon, 2004). Such latency is significant given the short time interval durations in the present study. To ensure this had no effect on experimental results, a photopic 1.5° circular stimulus was designed to maximally stimulate the MWS and LWS cones. MWS cones have a peak sensitivity at wavelengths near 530 nm and the LWS cones have a peak wavelength sensitivity at around 560 nm and as such, the visual stimulus was “yellow” ( $\lambda_d = 577$  nm), while the background, to ensure adaptation of the SWS cones, was “violet” ( $\lambda_d = -510$  nm; Kandel et al., 2000; Smithson & Mollon, 2004). Following from the Prenger (2005) study, a no-flicker (NFLK) and a flickering (FLK) stimulus condition was presented in phase with the time interval onset. During the NFLK condition, the circular stimulus was steadily presented for the appropriate duration, while during the FLK condition, the same circular target was modulated sinusoidally from the peak “yellow” ( $\lambda_d = 577$  nm) to the trough “violet” ( $\lambda_d = -510$  nm) background at a frequency of 15 cycles/sec (Hz) (See Appendix C). As timing accuracy is purportedly aided by flicker frequencies that are in phase with the stimulus presentation, a flicker frequency of 15 Hz (equal to 67 ms per cycle), was used so that the onset would be in



synchronized phase with the 400 and 1600 ms standard time interval durations (e.g., Westheimer, 2000).

### **Procedure**

Signal Detection Theory (SDT) attempts to describe the performance of individuals in the discrimination of a stimulus from some objective background, or standard stimulus using metrics that operate on signal-to-noise ratios in sensory- and decision making-based, assumable normal distributions (e.g., Macmillan & Creelman, 1991). In the present study, for example, SDT was applied to determine participants' timing sensitivity based on a duration discrimination judgment between a comparison and a standard time interval. The discrimination thresholds were determined using the Method of Constant Stimuli (MOCS), which randomly presented changing comparison time intervals to a constant standard interval. In the present study, accuracy (percent correct) based on traditional psychometric functions, includes the combined results of sensory, perceptual and motoric "response" processing characteristics while discriminability ( $d'$ ) refers to how well an individual can discriminate small differences in interval durations. SDT also allowed us to calculate decision bias ( $c$ ) which is a metric based on perceptual interpretation and cognitive decision making for a motoric response (see Ciaramitaro, Cameron and Glimcher, 2001). Calculation of these variables is discussed further in the **Data Analysis** section.

Subjects participated in one experimental session lasting approximately 120 minutes each. During the session, consent was obtained, preliminary assessment and psychometric measures were administered for about a 45-min period, followed by the psychophysical time perception task. The time perception tasks were performed in the Vision Laboratory at Lakehead University. After completing the psychophysical

measures, participants were debriefed and provided with a letter thanking them for their participation in the experiment. In the event participants were interested in learning the results of the study, the experimenter's contact information was also provided.

**Psychophysical time perception task.** Based on baseline data (Prenger, 2005) the MOCS test intervals that provided the best compromise for response range and time interval resolution were as follows: comparison test intervals against a 400 ms standard duration were 400, 467, 533, 600, 800 or 1000 ms; comparison test intervals against a 1600 ms standard duration were 1600, 1733, 1867, 2000, 2267 or 2533 ms. The standard and test intervals were presented randomly. These intervals were used for both the NFLK and FLK conditions. Interstimulus intervals were held at a constant 900 ms. The stimulus presentation sequence is graphically shown in Appendix C. The participants controlled the start of each presentation by pressing a button. The beginning and end of each trial was marked by a brief tone (500 Hz) to ensure the participants were prepared for trial onsets. Participants were not provided feedback as to whether their responses were correct or incorrect. Raw data were saved to a hard drive and manually entered into an Excel program. Subsequent calculations for proportion correct (PC), discriminability ( $d'$ ), decision bias ( $c$ ), slope, and threshold were done within Excel spreadsheets prior to figure generation and statistical analyses.

## Results

The broad scope of the present experiment involves a mixed between-subject and within-subject factor design to examine low- and high- end component operations in temporal processing and time perception. The between-subject factor is Group. In some analyses, there are two Group levels consisting of Control (non-ADHD subjects) and

ADHD-total. In other analyses, the ADHD group is further broken down into Inattentive and ADHD-other to investigate where differences exist as a function of symptom presentation. The Inattentive subgroup consists of subjects who present with symptoms of ADHD Predominantly Inattentive type. The ADHD-other subgroup consists of subjects who present with symptoms of ADHD Predominantly Hyperactive-Impulsive type or ADHD Combined type (see Section entitled “Symptomology” above). The within-subject factors are Duration, Stimulus, and Time Increment. Duration has two levels, 400-STI and 1600-STI, to represent, respectively, the two standard time interval levels that flank 1000 ms: 400 and 1600 ms. Stimulus has two levels, namely NFLK and FLK. Time Increment (TI) has five levels (TI-1, TI-2, TI-3, TI-4, and TI-5) whose proportion *contrast* values were defined as:  $(\text{test interval} - \text{standard interval}) / (\text{standard interval})$ . Note that the proportion contrast values were used when plotting and fitting the continuous psychometric and transducer functions, whereas statistical analyses used the ordinal levels designated TI-1 through TI-5. On plots of findings derived from statistical analyses, Time Increment Levels were depicted using these labels. The dependent variables include proportion correct (PC), discriminability ( $d'$ ), decision bias ( $c$ ), threshold, slope and working memory.

All data were examined to ensure accurate data entry and to identify any missing values, of which there were none. Four cases were identified as outliers due to random responding as evidenced by the anomalous trends depicted in the transducer functions derived from subject data. These data were removed from analyses.

### **Data Analysis**

Accuracy, as defined by the proportion of comparison trials correctly identified as “longer than” or “same as”, was calculated for each group by dividing the total number of

correct responses by the total number of trials. False alarms (FA) were incorrect responses to trials that were composed of the same comparison and standard durations (i.e., “blank” presentations incorrectly judged with a “longer than” response). The FA rates were used in calculating  $d'$  based on established ROC curves.

Proportion correct psychometric functions, where proportion correct versus time increment contrast for all conditions (400-STI, NFLK; 400-STI, FLK; 1600-STI, NFLK; 1600-STI, FLK) were also used to compare the performances of ADHD adults and non-ADHD controls. Difference thresholds for each condition were estimated from a proportion correct value of 0.5 (i.e., 50% correct measure) that was interpolated from a Weibull function that was fit to the psychometric data sets (e.g., Mortensen, 2002). Proportion correct values that fell below 0.5 were considered to be sub-threshold while those above the 0.5 cutoff were referred to as “supra-threshold”. Slopes of the fitted functions were used to convey information about performance efficiency (i.e., the higher the slope, the more efficient the discrimination performance; Macmillan & Creelman, 1991; Strasburger, 2001).

Sensory-based performance was ascertained by using transducer functions, where based on signal detection theory (SDT) methods, discriminability ( $d'$ ) was plotted as a function of time increment contrast for all conditions (400-STI, NFLK; 400-STI, FLK; 1600-STI, NFLK; 1600-STI, FLK). We then used these plots to compare the sensory performance to cognitive-decision and overall traditional PC performance of ADHD adults and non-ADHD controls.

Group mean proportion correct psychometric functions (i.e., PC vs. Time Increment Contrast) for all Duration and Stimulus levels are presented in Figs. 1 and 2. Plots of PC analyses for each and/or all factors are shown in Figs. 3-7. Transducer

functions, which plot discriminability ( $d'$ ) as a function of Time Increment Contrast are shown for all Duration and Stimulus levels in Figs 8 and 9. Plots of  $d'$  analyses for each and/or all factors are shown in Figs. 10-16. Decision bias plots are shown in Figs. 17 and 18. Plots of  $c$  analyses for each and/or all factors are shown in Figs. 19-22. Finally, bar graphs of the Group mean differences for slope and threshold (as defined by  $PC=0.5$ ) for all Duration and Stimulus levels are shown in Figs. 23 - 24.

Repeated measures ANOVAs were used to determine Group differences in PC,  $d'$ , and  $c$  for all Duration, Stimulus and TI-levels. Least Significant Difference (LSD) post hoc tests were used to characterize significant effects. One-way ANOVAs were used to determine group differences in slope, threshold and, working memory. Level of significance was set to  $p \leq 0.5$ .

**Proportion Correct (PC).** To assess differences between the Control group and the ADHD-total group, a four factor 2 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA with Group as the between-subjects factors was used. A significant effect of Duration on PC was revealed,  $F(1, 26) = 75.609, p < .05$ , partial  $\eta^2 = .74$ . Mean values show that, overall, proportion correct was better for 1600-STI ( $M = .584$ ) than for 400-STI ( $M = .336$ ). Again, not surprisingly, a significant main effect was found for Time Increment Level,  $F(4, 104) = 94.317, p < .05$ , partial  $\eta^2 = .78$ . Proportion correct increases significantly as the time increment level increases.

A post hoc one-way ANOVA revealed that PC was significantly greater for Control than for ADHD-total with the 1600-STI NFLK TI-5 ( $F(1, 26) = 4.525, p < .05$ ), while ADHD had a significantly higher proportion correct compared to Control for the 400-STI FLK TI-1 ( $F(1, 26) = 7.581, p < .05$ ). These results suggest that accuracy on the part of the Control group is better than the ADHD-total group with durations greater

than threshold. Findings do suggest that, for 400-STI FLK TI-1, the ADHD-total group had a greater proportion correct compared to Controls. This result is somewhat unexpected considering previous findings of time perception deficits on the part of ADHD individuals (e.g. Toplack & Tannock, 2005). A possible explanation of this result might be a less conservative response pattern on the part of the ADHD-total group than the Control group which might bring about subthreshold (i.e., less salient stimuli) Group distinctions (see Section Decision Bias below). Figure 1 shows an overall higher proportion correct for the 1600-STI at the lowest time increment levels compared to the 400-STI. Despite this difference, accuracy is equal at high time interval levels for both the 400-STI and the 1600-STI. This is not unexpected as TI-5 for the 400-STI is at the one second mark, and is above one second for the 1600-STI (see Section Low- and High-End Component Operations in Temporal Processing). When comparing the 400-STI panel to the 1600-STI panel, the trend shift of the 400-STI psychometric functions towards the right compared to the 1600-STI psychometric functions indicate that both groups are less sensitive (i.e. higher threshold) to changes in duration for the 400-STI.

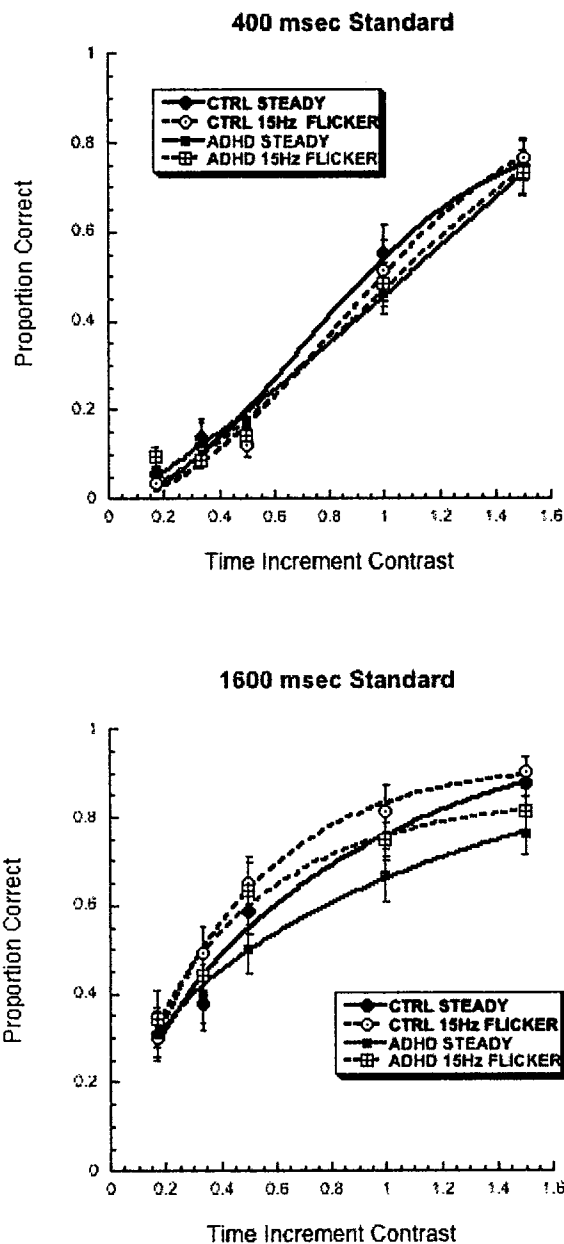


Figure 1. Proportion Correct (PC) as a function of Time Increment Contrast for Control (blue data and fits) and ADHD-total groups (red data and fits). The NFLK (FLK) stimulus condition is shown with solid (open) data symbols and continuous (stippled) Weibull fits. Most obvious is the greater proportion correct of trial responses at suprathreshold levels for the 1600-STI (lower panel) on the part of Controls compared to ADHD-total. The continuous function is a Weibull fit to the data. Error bars represent  $\pm$  1 SEM.

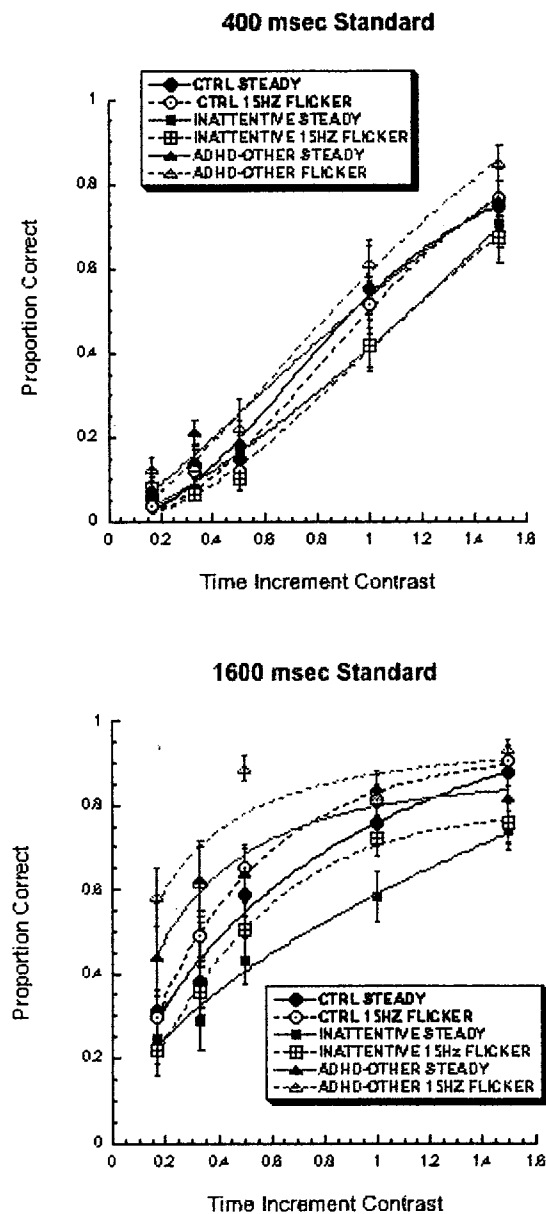


Figure 2. Proportion Correct (PC) as a function of Time Increment Contrast for Control (blue data and fits), Inattentive groups (red data and fits) and, ADHD-Other (green data fits). The NFLK (FLK) stimulus condition is shown with solid (open) data symbols and continuous (stippled) Weibull fits. Upper and lower panels show measurements with 400- and 1600-STI. Differences between 400-STI and 1600-STI (cf. upper and lower panels) are evident in both the lower slope and the larger separation between group trends for the 1600-STI. A greater proportion or durations were responded to correctly with 1600-STI. Error bars represent  $\pm 1$  SEM.



No significant main effect was found for Stimulus ( $F(1, 26) = .004, p = \text{n.s.}$ ), nor was one found for Group ( $F(1, 26) = .007, p = \text{n.s.}$ ). Significant interactions of Duration and Stimulus,  $F(1, 26) = 7.257, p < .05$ , partial  $\eta^2 = .22$  (Fig. 2); and Duration and Time Increment Level,  $F(4, 104) = 9.597, p < .05$ , partial  $\eta^2 = .27$  (Fig. 3) were found.

The Duration x Stimulus interaction reveals differences in accuracy that were dependent on whether or not the stimuli were flickering and at what duration the stimuli were presented for. Accuracy was greater for 400 -STI in the NFLK condition while the FLK condition showed improved accuracy with 1600-STI. Also, while differences in proportion correct for the 400 -STI and the 1600 ms-STI were evident at small time increment contrasts, these differences disappeared at larger increment levels. Detailed descriptions of these interactions accompany Fig. 3 and 4 below.

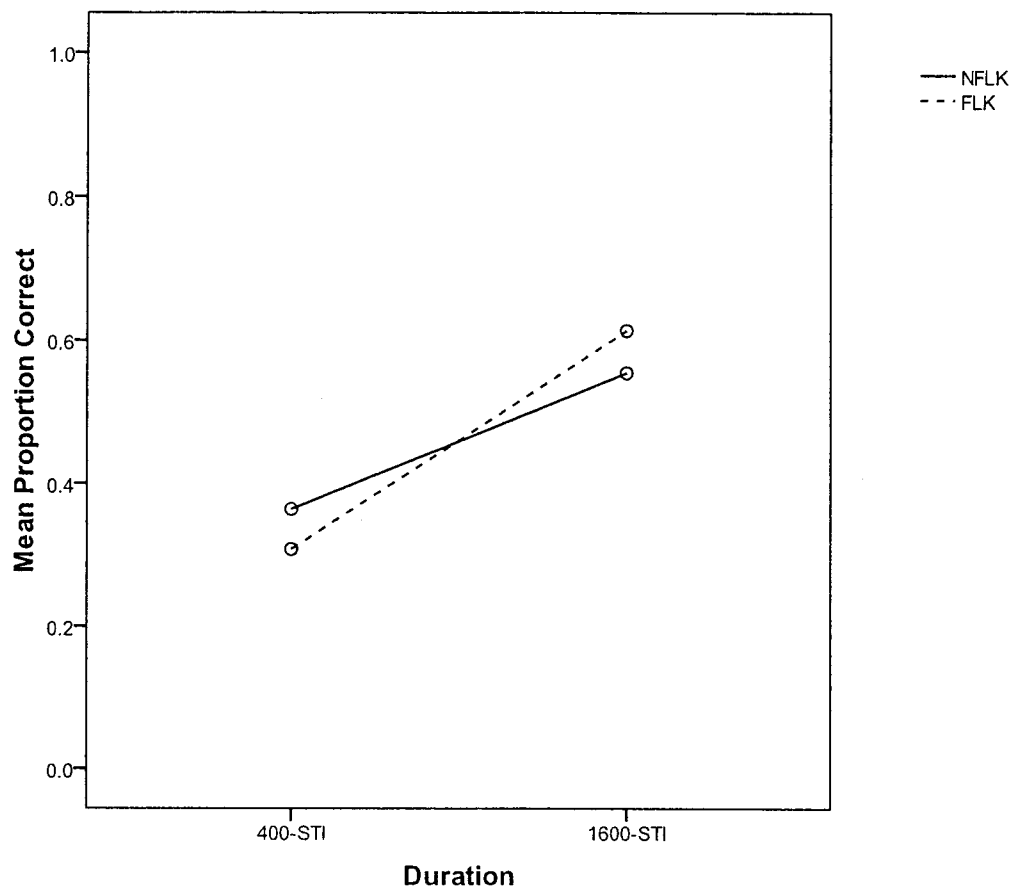


Figure 3. Proportion Correct (PC) interaction effects between Duration and Stimulus (Control and ADHD-total groups combined). NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Proportion correct is higher in the NFLK condition for the 400-STI while proportion correct is higher in the FLK condition for 1600-STI.

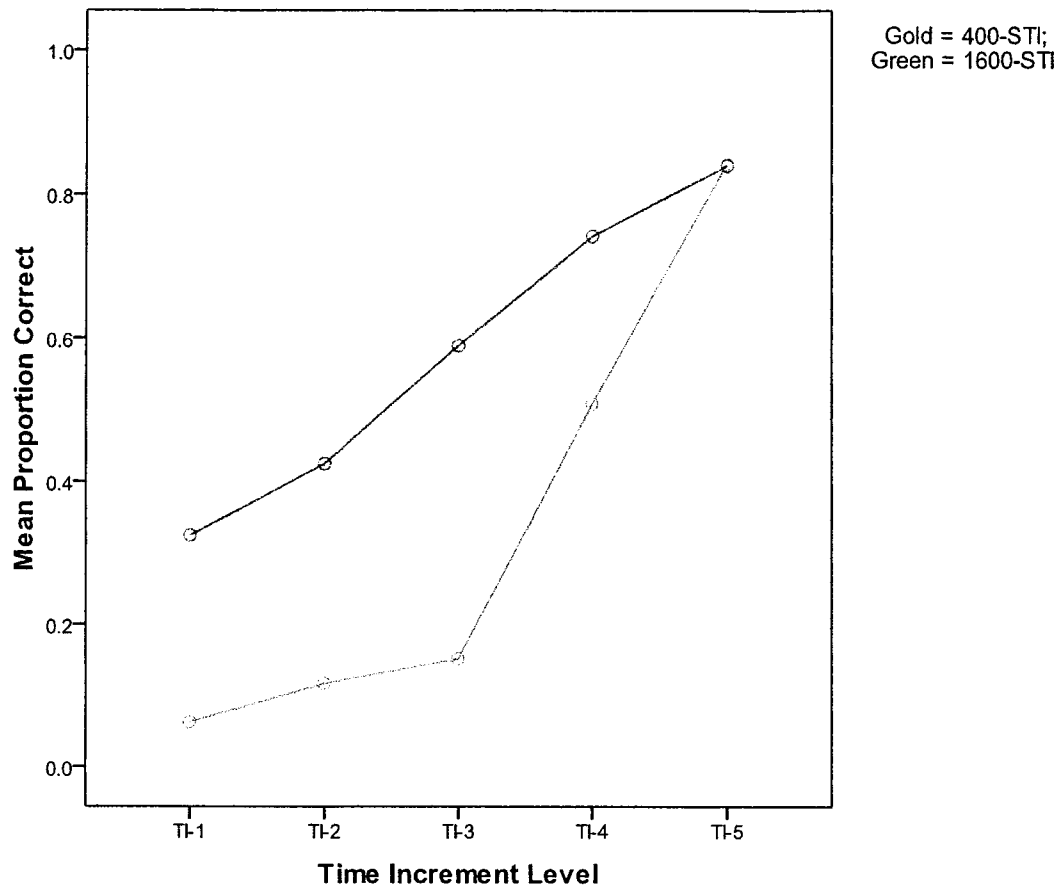


Figure 4. Mean proportion correct (PC) interactions between Time Increment Level and Duration for Control and ADHD-total groups combined. This figure demonstrates a natural trend in research – performance, in this case, accuracy, increases as difference saliency increases. At smaller time increment levels, proportion correct is greater for the 1600-STI (denoted by green symbols) than for the 400-STI (denoted by gold symbols). As time interval contrast increases, this difference disappears and proportion correct for both standard time intervals are equal. In the present study, this effect is also apparent in discriminability performance and in decision bias.

To determine if differences in symptom presentation between ADHD subtypes (see section entitled Symptomology) is reflected in accuracy, an additional four factor 3 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA was conducted, with Group as the between-subjects factors. The three levels of Group include Control, Inattentive and ADHD-Other. Analysis revealed a significant effect of Duration on PC,  $F(1, 25) = 72.203, p < .05, \text{partial } \eta^2 = .74$ . Mean values show that, overall, proportion correct was better for 1600 STI ( $M = .603$ ) than for 400-STI ( $M = .345$ ). A significant effect was found for Time Increment Level. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom  $F(4, 104) = 94.317, p < .05, \text{partial } \eta^2 = .73$ . Proportion correct increases significantly as the time increment level increases. A one-way ANOVA and post hoc LSD tests revealed that proportion correct was significantly greater for ADHD-other compared to both Control and Inattentive in responding to the 400-STI FLK TI-3 ( $F(2, 25) = 3.413, p < .05$ ); 1600-STI NFLK TI-2 ( $F(2, 25) = 3.617, p < .05$ ); 1600-STI FLK TI-1 ( $F(2, 25) = 3.617, p < .05$ ); and, the 1600-STI FLK TI-3 ( $F(2, 25) = 5.529, p < .05$ ). Accuracy was better for ADHD-other than for Control in responding to the 400-STI FLK TI-1 ( $F(2, 25) = 4.876, p < .05$ ). Control had a significantly higher proportion correct compared to Inattentive in responding to the 1600-STI FLK TI-5 ( $F(2, 25) = 3.552, p < .05$ ). These findings suggest that, for both 400- and 1600-STI, the ADHD-other group had a greater proportion correct compared to Controls for durations below threshold levels. Results also indicate that accuracy on the part of the Control group is better than the Inattentive group for durations above threshold levels. These results are depicted in Fig. 2.

No significant effect was found for the between-subjects factor of Group ( $F(1, 25) = 1.845, p = .n.s.$ ), nor was one found for Stimulus ( $F(1, 25) = .120, p = n.s.$ ). Significant interactions of Duration and Group  $F(2, 25) = 4.063, p < .05, \text{partial } \eta^2 = .25$  (Figure 5); Duration and Stimulus,  $F(1, 25) = 5.404, p < .05, \text{partial } \eta^2 = .18$  (Figure 6); and, Duration and Time Increment level,  $F(1.265, 100) = 8.032, p < .05, \text{partial } \eta^2 = .24$  (Figure 7) were found. The assumption of sphericity was violated for each of these interactions. The Huynh-Feldt correction was used to correct the degrees of freedom.

These interactions reflect both the greater accuracy of ADHD-Other group over Control group for the 400-STI and over both Control and Inattentive for some levels of the 1600-STI. Controls, however, are shown to have a higher proportion correct for the 1600-STI. The FLK condition appears to exert its effect for the 1600-STI and while proportion correct is highest for the 1600-STI at smaller time increments, no differences were apparent at the large time increments. Detailed descriptions of these interactions are seen in Figs. 5 – 7 below.

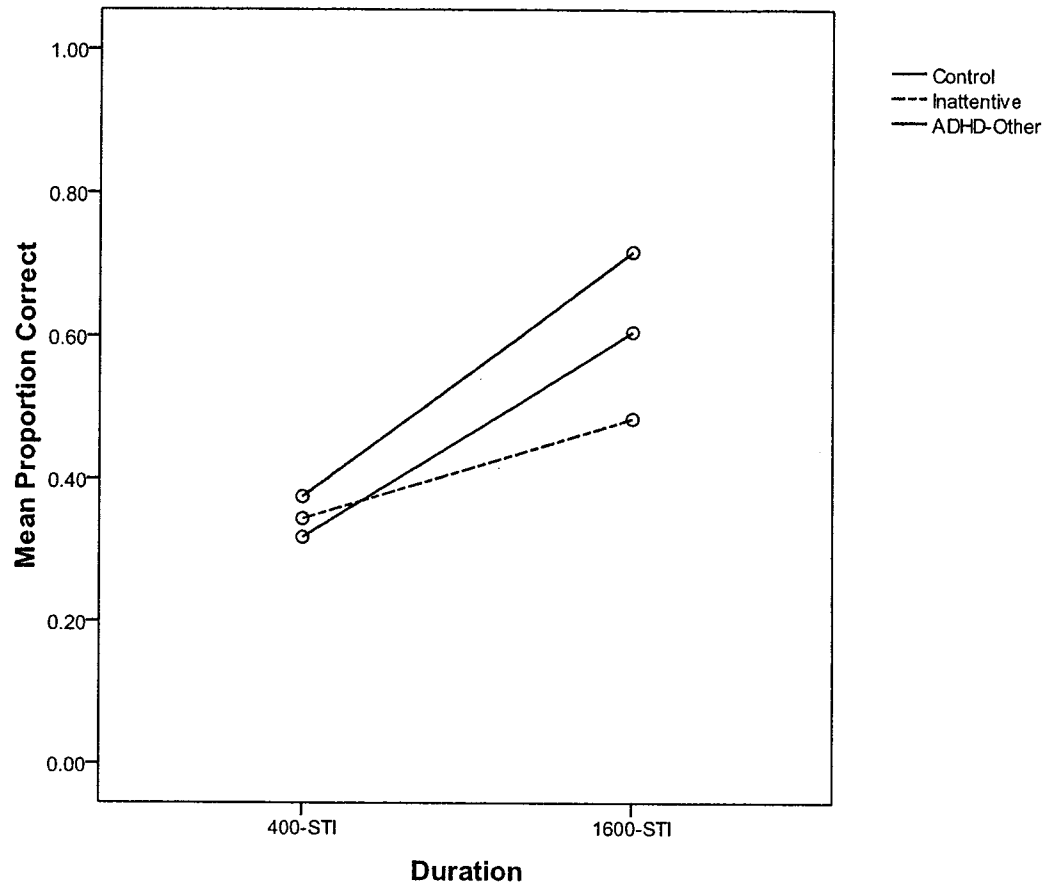


Figure 5. Mean proportion correct (PC) as a function of Duration. Controls (blue), Inattentive (dashed red) and ADHD-Other (continuous red) groups are shown. Differences in accuracy between ADHD-Other and Control is seen at 400-STI, but not as great as the separations in performance that occurred with 1600-STI. Here, ADHD-Other performed better than both Control and Inattentive Groups.

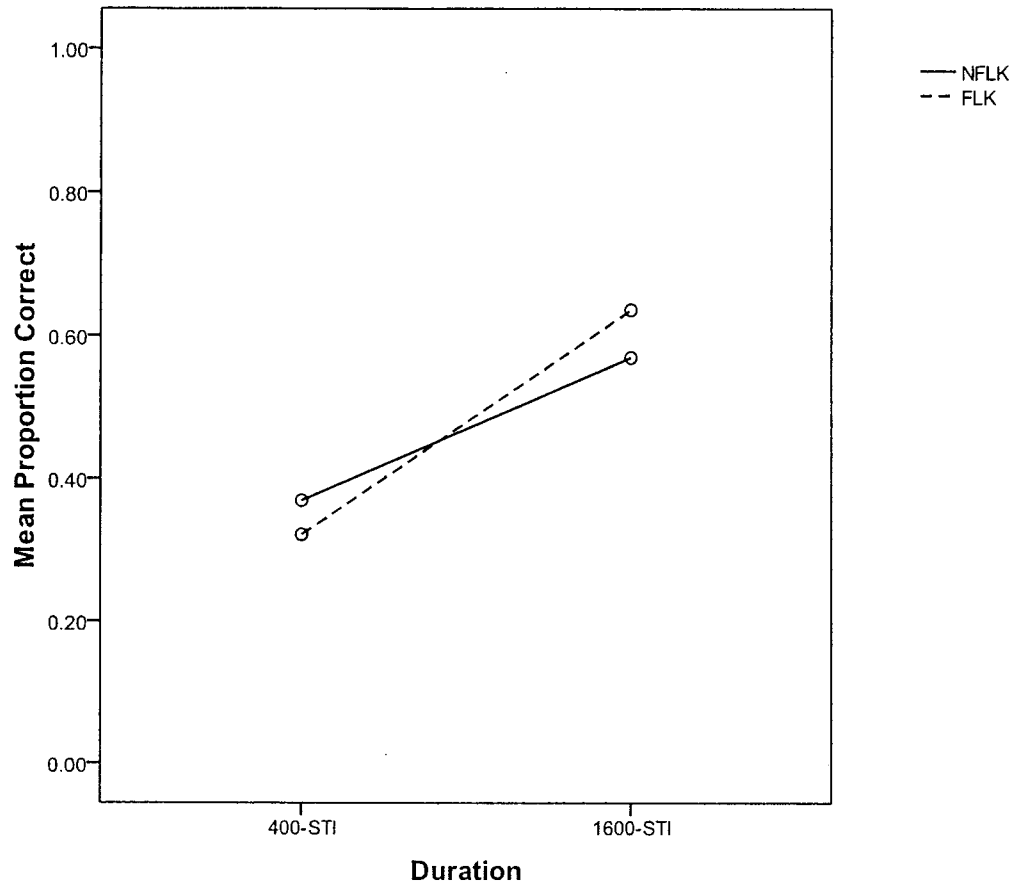


Figure 6. Mean proportion correct (PC) interactions between Duration and Stimulus conditions for Control, Inattentive and ADHD-other groups combined. NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Proportion correct is higher with the 400-STI NFLK condition while proportion correct is higher with the 1600-STI FLK condition.

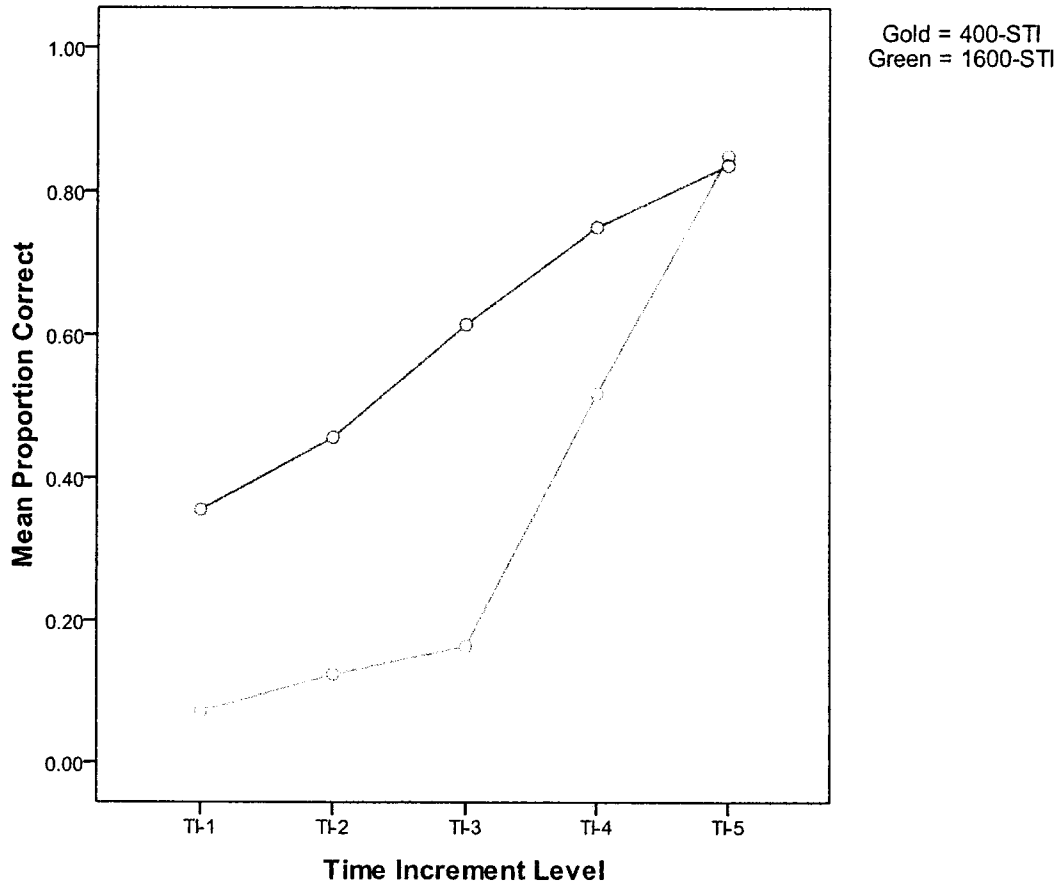


Figure 7. Mean proportion correct (PC) interactions between Time increment Level and Duration (Control, Inattentive and ADHD-Other groups combined). At small time increment contrasts, proportion correct is higher for the 1600-STI (denoted by green symbols) than for the 400-STI (denoted by gold symbols). Note the trend: at the largest time increment level proportion correct for both standard time intervals are equal (see Fig. 4 caption).



**Discriminability ( $d'$ )** To assess differences in  $d'$  between Control and ADHD-total, a 2 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA with Group as the between-subjects factor revealed a significant effect of Group,  $F(1, 26) = 6.758, p < .05, \text{partial } \eta^2 = .21$ . Mean values show that, overall, time increment discrimination performance was better for the Control group ( $M = 1.347$ ) than for the ADHD-total group ( $M = 0.936$ ). A significant within-subject effect was found for Time Increment Contrast. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom,  $F(2.047, 104) = 150.642, p < .05, \text{partial } \eta^2 = .85$ . Post hoc LSD comparisons revealed that each time increment is significantly different from all four other time increments with respect to discriminability. Not surprisingly, discrimination performance increases significantly as the time increment levels increases.

Results of a post-hoc one-way ANOVA revealed group differences in discriminability as a function of time increment level. Specifically, discrimination performance was significantly better for Control than for ADHD on the following time increments: 1600-STI NFLK TI-3 ( $F(1, 26) = 8.401, p < .05$ ); 1600-STI NFLK TI-5 ( $F(1, 26) = 6.493, p < .05$ ); 1600-STI FLK TI-2 ( $F(1, 26) = 6.694, p < .05$ ); 1600-STI FLK TI-4 ( $F(1, 26) = 4.921, p < .05$ ); and, 1600-STI FLK TI-5 ( $F(1, 26) = 6.162, p < .05$ ). These results show that the main effect of Group is due to better discrimination performance by Controls for the 1600-STI for both stimulus conditions and mainly at suprathreshold time increment levels (i.e.  $TI \geq 3$ ). These results also indicate that discriminability on the part of the Control group was better at subthreshold time increment levels for the flicker condition than the non-flicker condition. This suggests

some effect of flicker on performance at small increment contrasts for Controls (see Figure 8).

No significant effect was found for Duration ( $F(1, 26) = 2.437, p = .n.s.$ ), nor was one found for Stimulus ( $F(1, 26) = 3.083, p = n.s.$ ). These findings are also represented in Figure 8, where no shifts in transducer functions along the x-axis are seen when comparing the 400-STI upper panel to 1600-STI lower panel.

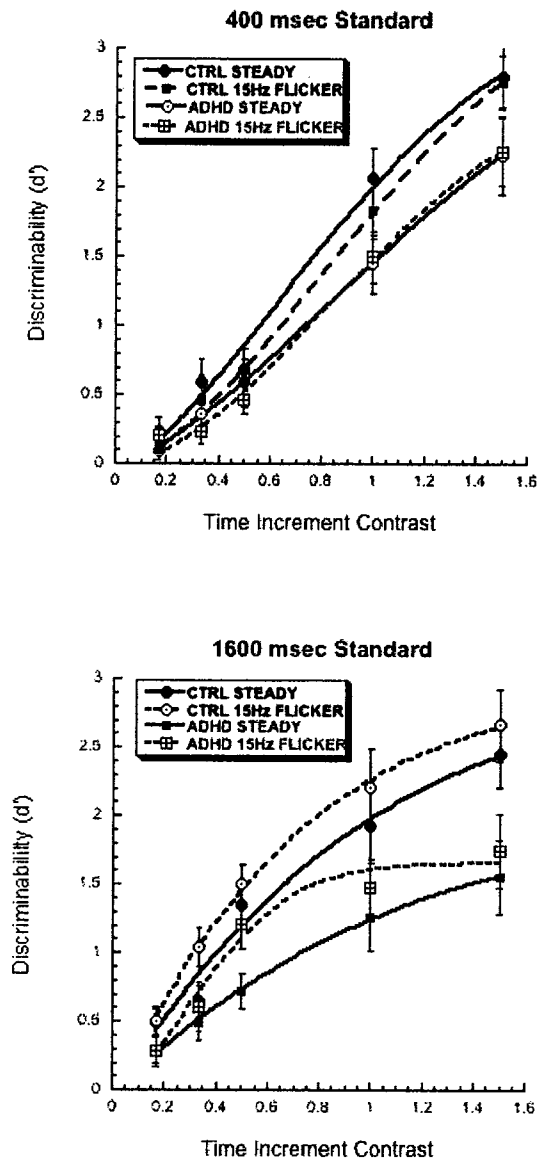


Figure 8. Discriminability as a function of Time Increment Contrast for Control and ADHD-total groups. No significant differences were found between groups for the 400 ms standard time interval (upper panel), however the significant differences for the 1600 standard time interval (lower panel) are apparent, at high time increment contrasts. The continuous transducer function is a Weibull curve fit to the data. Error bars represent  $\pm 1$  SEM.

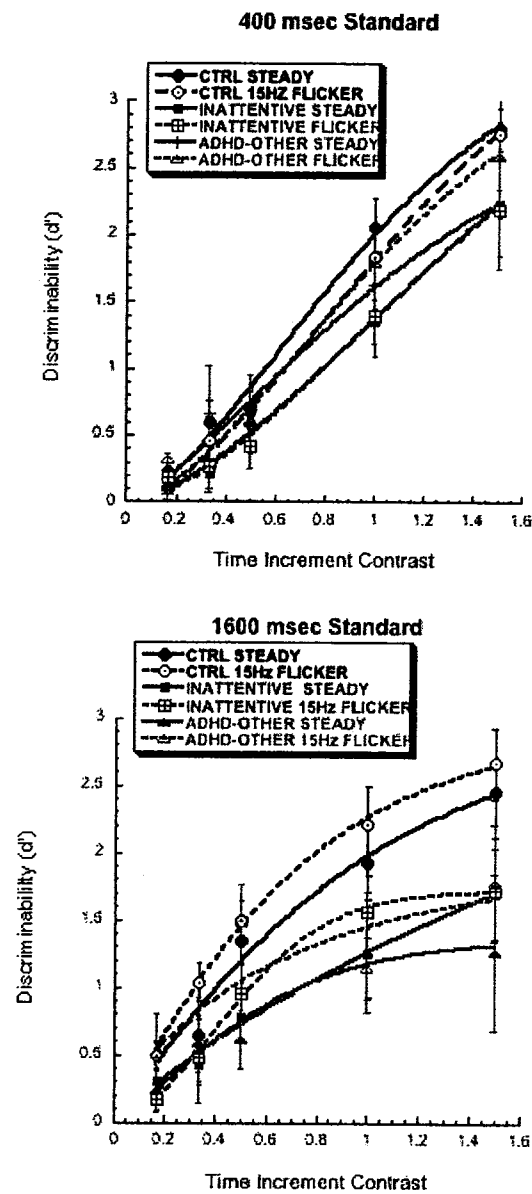


Figure 9. Discriminability ( $d'$ ) as a function of Time Increment Contrast for Control (blue data and fits), Inattentive groups (red data and fits) and, ADHD-Other (green data fits). The NFLK (FLK) stimulus condition is shown with solid (open) data symbols and continuous (stippled) fits. Again, no significant differences were found between groups for 400-STI (upper panel). Controls performed significantly better than Inattentive and ADHD-other at the larger time increments for the 1600-STI (lower panel). The continuous transducer function is a Weibull fit to the data. Error bars represent  $\pm 1$  SEM.

Significant interactions of Group x Time Increment Level,  $F(4, 104) = 3.156, p < .05$ , partial  $\eta^2 = .11$  (See Figure 10); Duration x Stimulus,  $F(1, 26) = 6.923, p < .05$ , partial  $\eta^2 = .21$  (See Figure 11); and, Duration x Time Increment Level,  $F(4, 104) = 18.110, p < .05$ , partial  $\eta^2 = .41$  (See Figure 12) were found.

Taken together these interactions indicate that while Controls show higher discrimination performance, this increase in performance is most evident for the 1600-STI, particularly with respect to discrimination of the larger time increments levels rather than the smaller levels. Furthermore, for both the Control group and the ADHD-total group, discrimination performance is enhanced by the flicker stimulus for the 1600-STI but has no effect on discrimination performance for the 400-STI. Detailed descriptions of interactions are found in the respective figure captions.

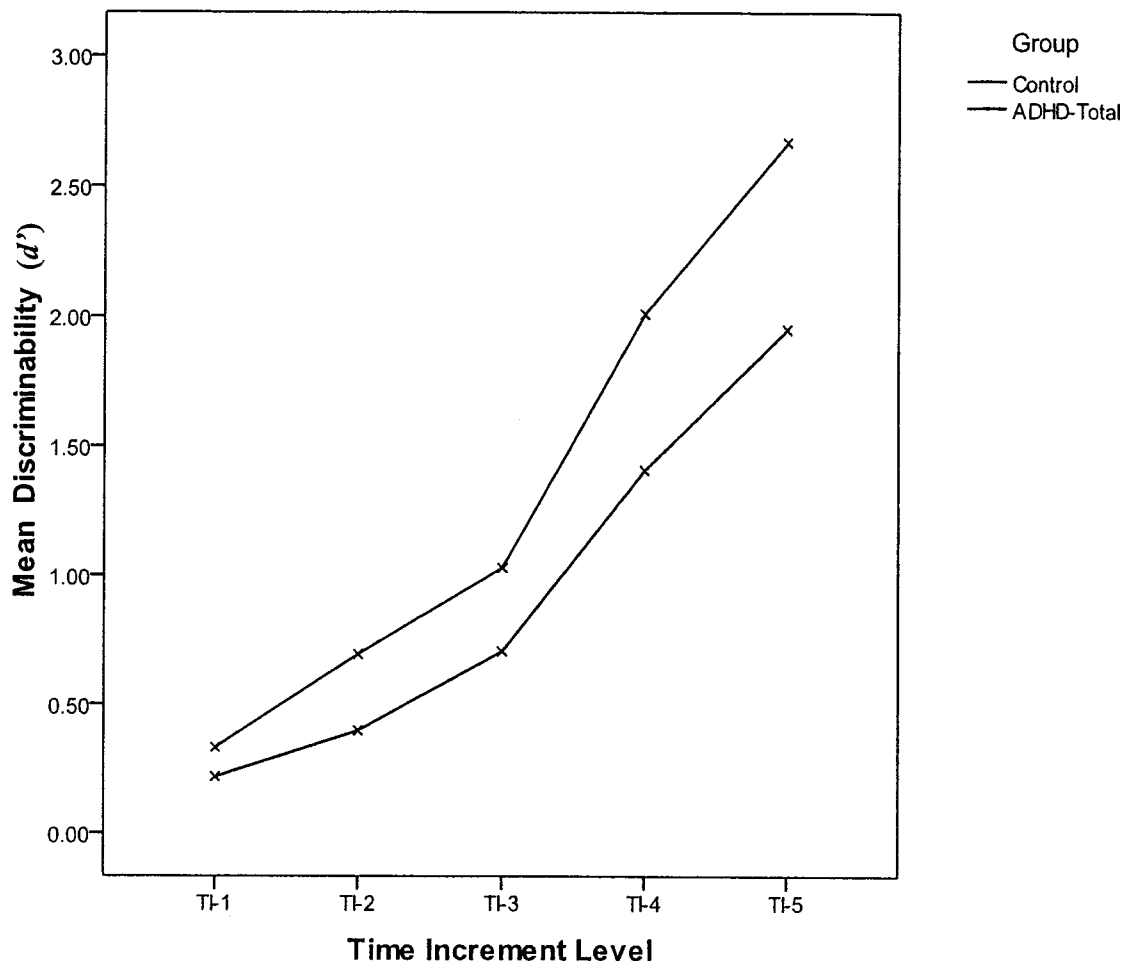


Figure 10. Mean Discriminability as a function of Time Increment Levels. Control (ADHD-Total) measurements are shown in blue (red). The interaction between time increment level and Group suggests that some differences in discriminability between the Control and ADHD groups can be accounted for by performance at different time increment levels (versus performance across all increment levels). This figure shows a much higher discriminability on the part of the Control group at the largest time increment level than at the smaller contrast levels. Performance differences at the large increment levels may contribute most greatly to the significant effect of group on discriminability.

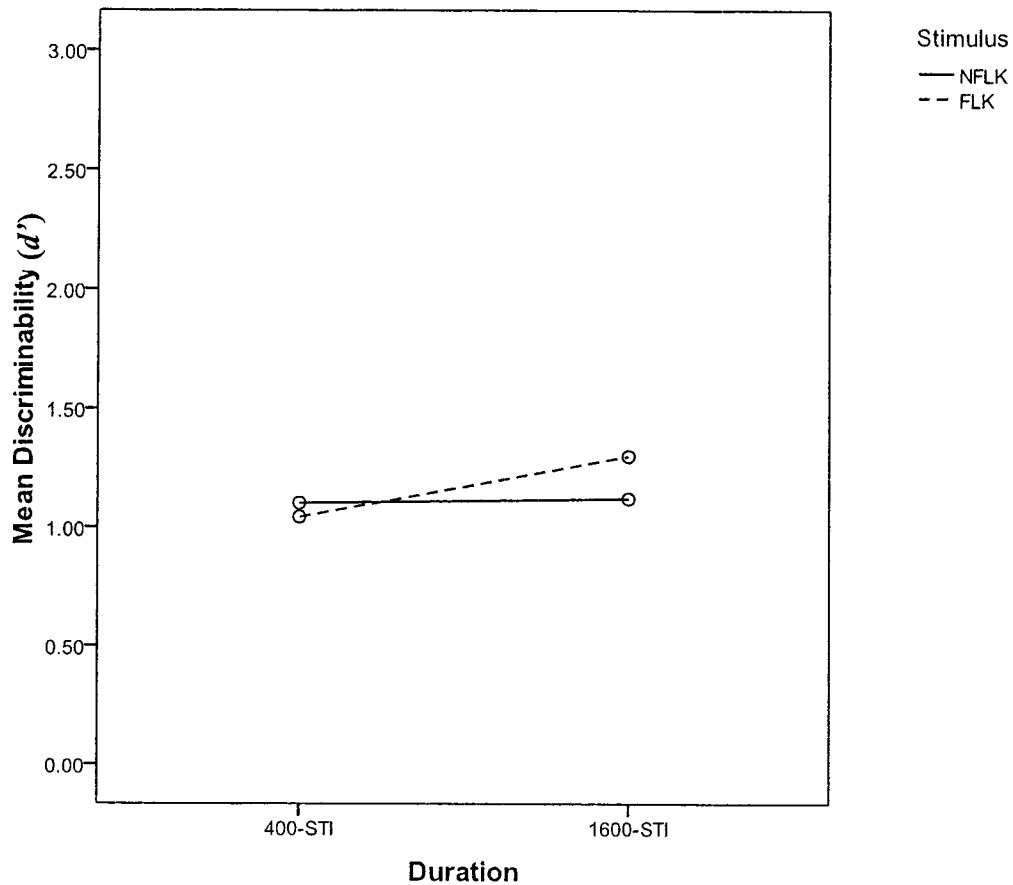


Figure 11. Sensory discriminability ( $d'$ ) interaction effects between Duration and Stimulus (Control and ADHD-Total groups combined). NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Note that the flicker stimulus condition improves discriminability for the 1600-STI (see Section Duration Discrimination and Temporal Information Processing (TIP) above), while no sensory performance improvement is seen with 400-STI flicker entrainment.

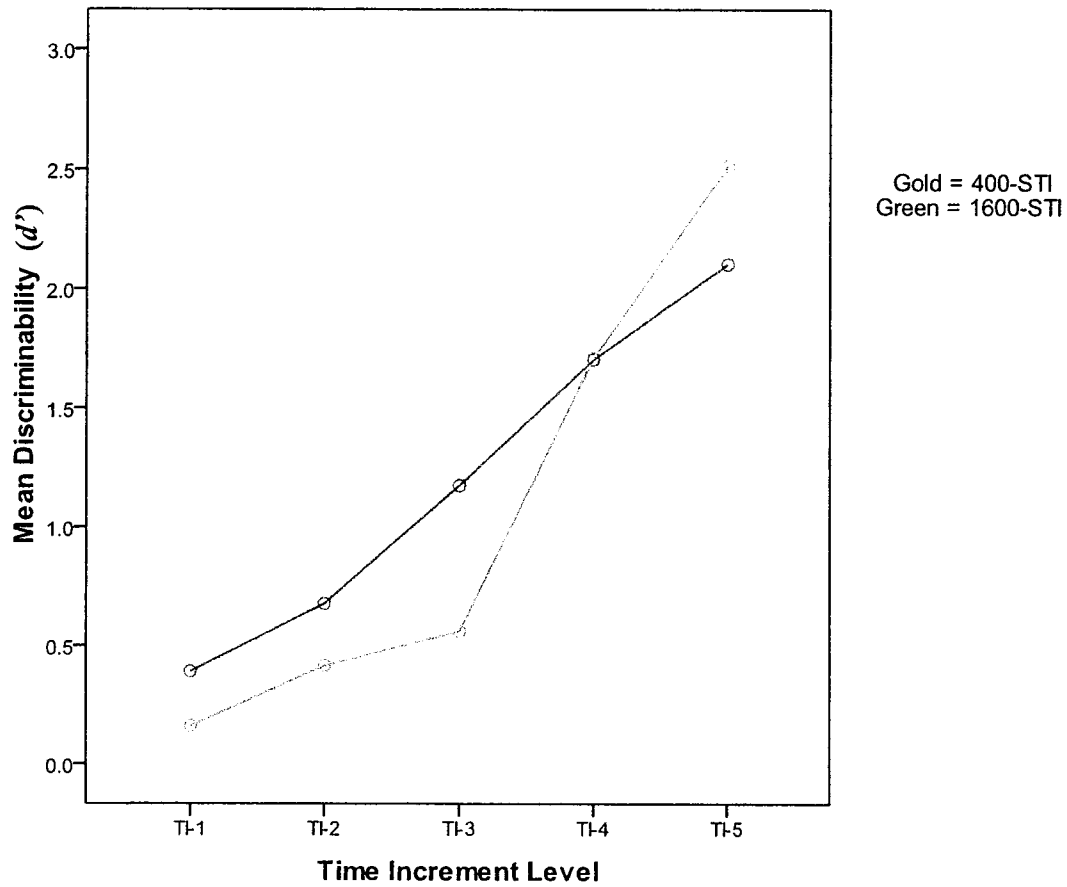


Figure 12. Sensory discriminability ( $d'$ ) interaction effects between Duration and Time Increment Level (Control and ADHD-total groups combined). Although discriminability increases as time increment level for both durations, the pattern of the increase differs between 400- (gold) and 1600- (green) STI. While discriminability increases gradually for 1600-STI, there is a dramatic rise in discriminability with 400-STI after TI-3.



To determine if differences in symptom presentation between ADHD subtypes (see section entitled Symptomology) is reflected in sensory discrimination performance, we ran an additional four factor 3 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA with Group as the between-subjects factors. The three levels of Group include Control, Inattentive and ADHD-Other. Analysis revealed a significant Group effect,  $F(1, 25) = 3.382, p = .05, \text{partial } \eta^2 = .21$ . Mean values show that, overall, time increment discrimination performance was better for the Control group ( $M = 1.347$ ) than for the ADHD-Other group ( $M = 0.936$ ). Post hoc multiple comparisons were performed using the LSD test. The Control group ( $M = 1.347$ ) performed significantly better than did the Inattentive group ( $M = 0.896$ ). A significant effect of Stimulus on  $d'$ ,  $F(1, 25) = 5.044, p < .05, \text{partial } \eta^2 = .17$  was also found. Mean values show that, overall, time increment discrimination performance was better for FLK ( $M = 1.129$ ) than for NFLK ( $M = 1.043$ ). With respect to Stimulus, no significant differences were found between Control and ADHD-other, nor were any found between Inattentive and ADHD-other. A significant within-subject effect was found for TI levels. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom,  $F(2.128, 104) = 97.677, p < .05, \text{partial } \eta^2 = .80$ .

Results of a post hoc one-way ANOVA revealed group differences in discriminability as a function of time increment levels. Discrimination performance was significantly better for Control than for both Inattentive and ADHD-other on the 1600-STI NFLK TI-3 ( $F(2, 25) = 4.179, p < .05$ ). Performance was also significantly better for Controls compared to ADHD-other on the 1600-STI FLK TI-5 ( $F(2, 25) = 3.479, p < .05$ ). No significant effect was found for Duration ( $F(1, 25) = .451, p = .n.s.$ ). These

results can be ascertained from the Control and ADHD-Inattentive transducer functions shown in Figure 9.

An interaction of Group, Stimulus and Time Increment Level,  $F(8, 100) = 2.104$ ,  $p < .05$ , partial  $\eta^2 = .14$  (Figure 13 and Figure 14) was found and an interaction of Duration and Stimulus approached significance,  $F(1, 25) = 4.186$ ,  $p = .051$ , partial  $\eta^2 = .14$ . A significant interaction of Duration and Time Increment Level,  $F(4, 100) = 15.497$ ,  $p < .05$ , partial  $\eta^2 = .38$  (See Figs. 15 and 16, respectively) was also found.

Taken together these interactions indicate that for all groups, discrimination performance is enhanced by flickering stimuli for the 1600-STI but has no effect on discrimination performance for the 400-STI. Discriminability gradually increases for 1600-STI, while for 400-STI, discriminability dramatically increases after reaching intermediate (e.g., TI-3) time increment levels. These interactions also show that Controls performed significantly better than the Inattentive group in the NFLK condition and relatively better than the ADHD-other group. In the NFLK condition, the ADHD-other group performed more like controls at smaller time increments and more like the Inattentive group at larger TI levels. Controls also performed better than the Inattentive and ADHD-other groups in the FLK condition and the performance pattern of the ADHD-other group is the reverse of the pattern seen in the NFLK condition. Detailed descriptions of interactions accompany Figures 13-14 below.

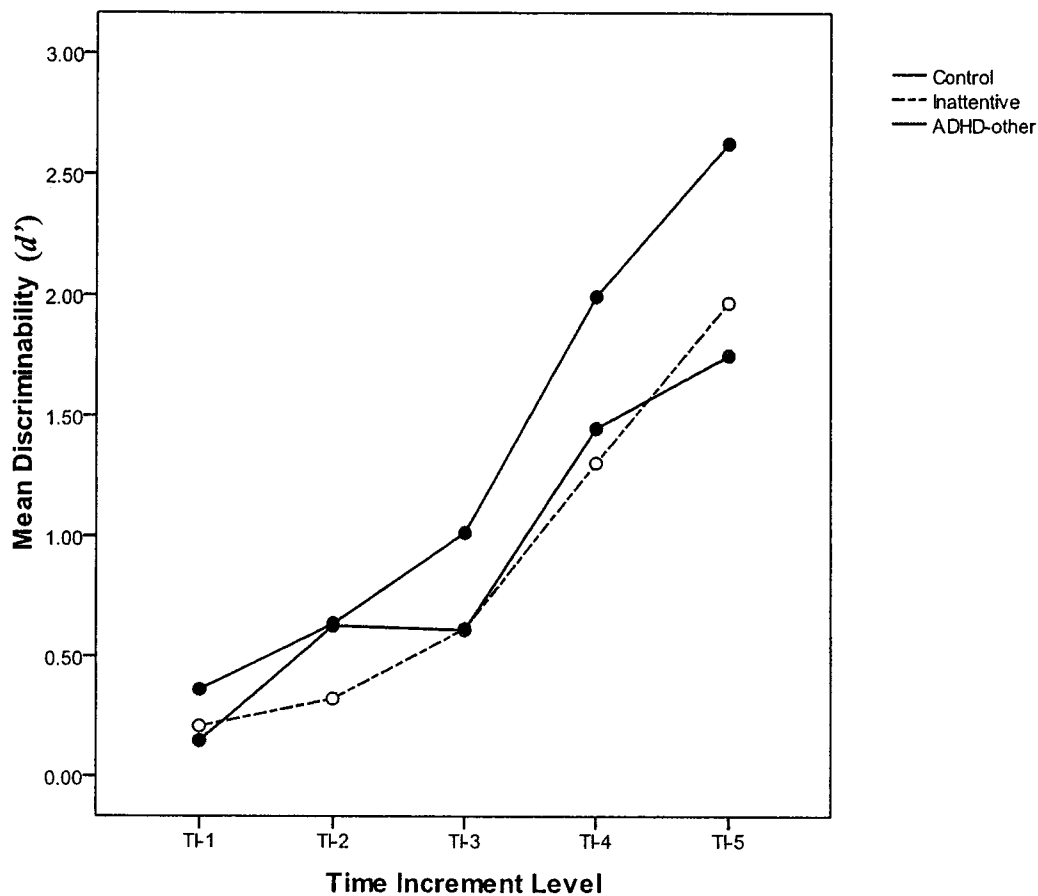


Figure 13. Group discriminability ( $d'$ ) as a function of Time Increment Level with NFLK Stimuli. Discrimination performance is generally better for the Control group (blue) compared to the Inattentive (red, open circles) and ADHD-other (red, closed circles) groups across time increments for the Steady condition. The ADHD-other group shows an inconsistent but steadily increasing pattern while the Inattentive group has a slightly lower performance than the ADHD-other group and a much lower performance than the Control group for the steady condition.

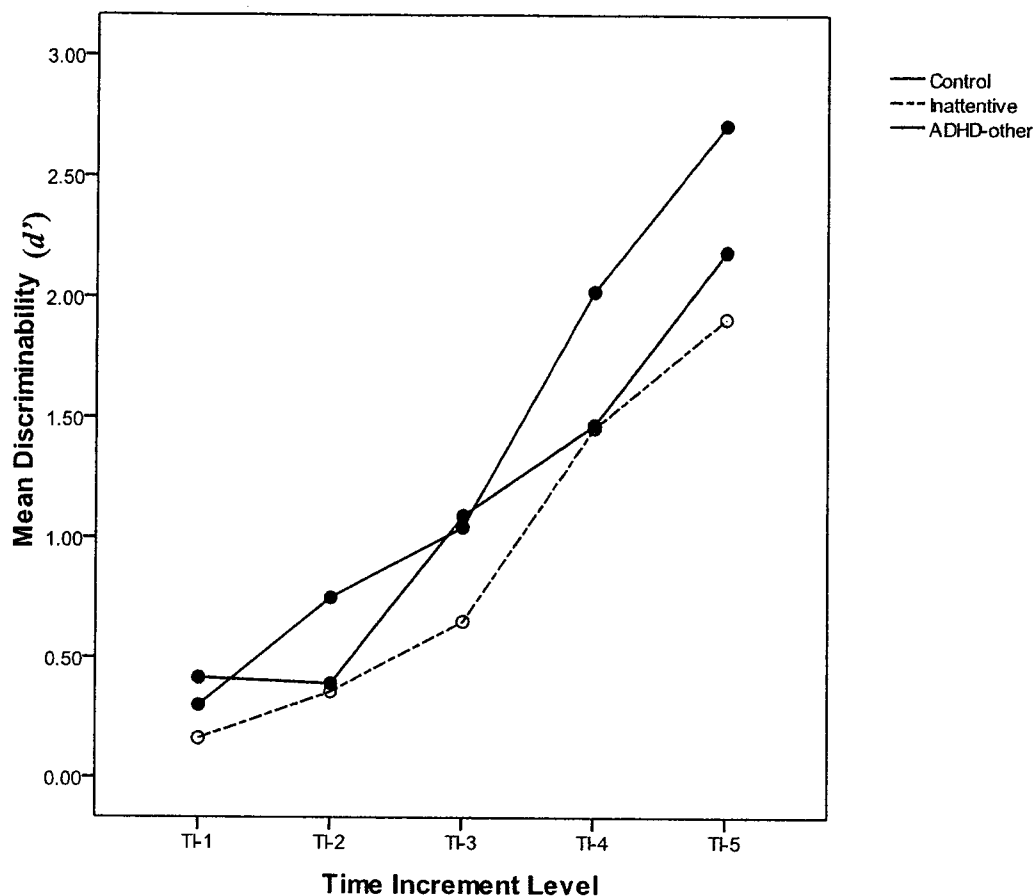


Figure 14. Group discriminability ( $d'$ ) as a function of Time Increment Level with FLK Stimuli. Performance for the Control group (blue) for the flicker condition is similar to that group's performance for the steady condition. For the ADHD-other group (continuous red) however, compared to NFLK, the flickering stimulus seems to decrease performance at smaller time increments while increasing performance as time increments got larger. At the larger time increment levels, flicker seems to have an effect on performance for this group (see Section Duration Discrimination and Temporal Information Processing (TIP) above). Discrimination performance for the Inattentive (dashed red) group appears not to differ between steady and flicker conditions, perhaps an indication of some sensory deficit on the part of the Inattentive group.

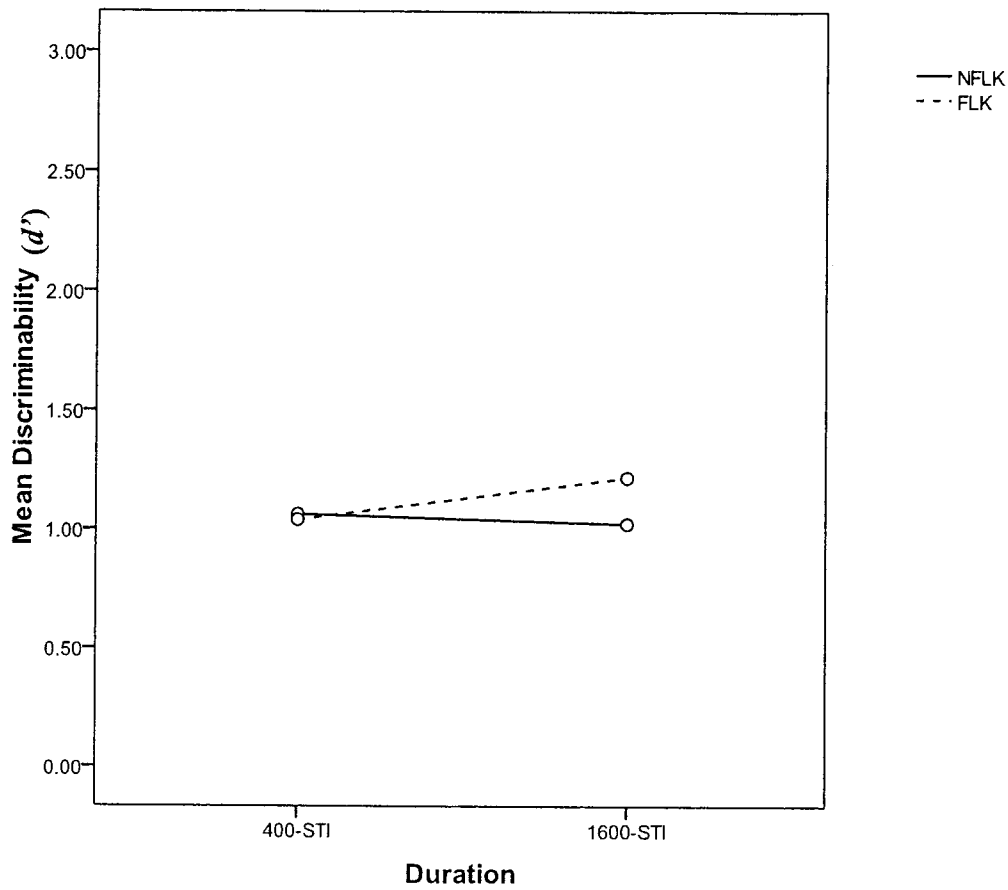


Figure 15. Sensory discriminability ( $d'$ ) interaction effects between Duration and Stimulus (Control, Inattentive and ADHD-other groups combined). NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Note that FLK exerts its effect of improving discriminability for 1600-STI (see Section Duration Discrimination and Temporal Information Processing above), while being ineffective with the 400-STI duration.

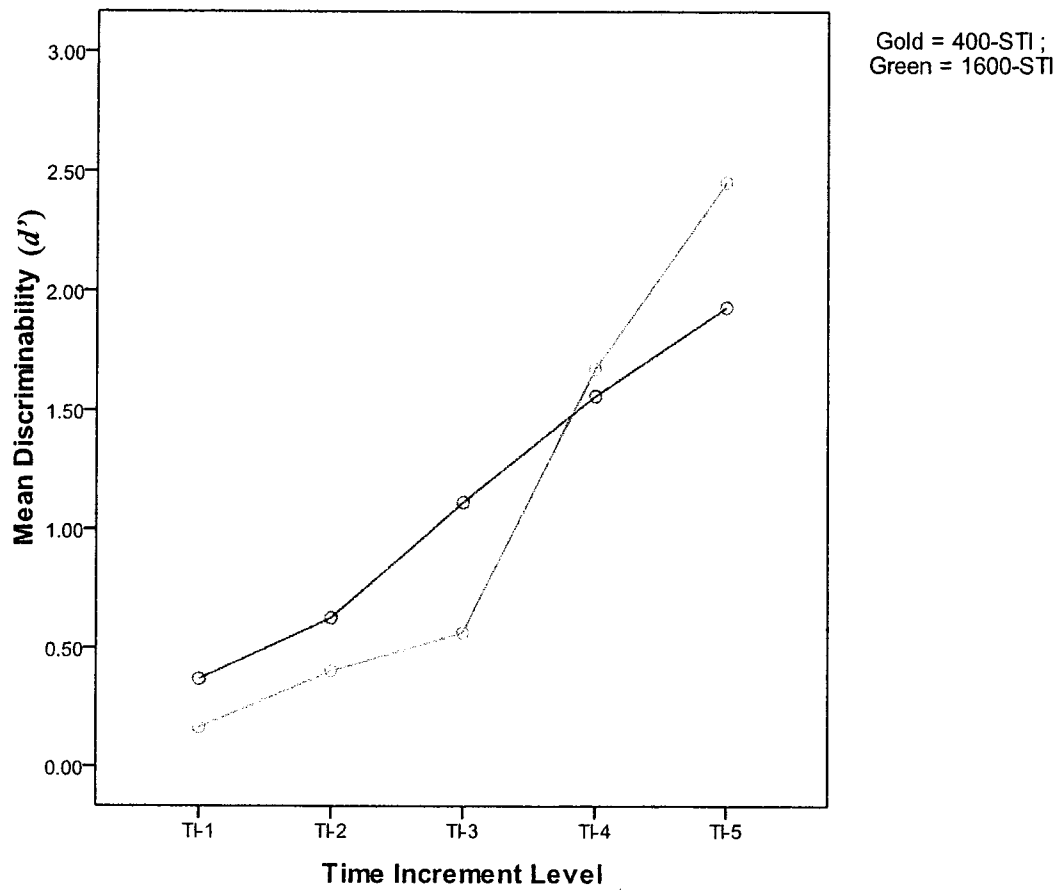


Figure 16. Sensory discriminability ( $d'$ ) interaction effects between Duration and Time Increment Level for Control, Inattentive and ADHD-other groups combined. Discriminability increases as TI increases for both durations; however, discriminability is seen to increase gradually for 1600-STI (green) while discriminability for 400-STI (gold) increases dramatically as time increment levels increase.

**Decision Bias (*c*).** To assess differences between the Control group and the ADHD-total group, a four factor 2 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA with Group as the between-subjects factor was conducted. Analysis revealed a significant effect of Duration on *c*,  $F(1, 26) = 149.176, p < .05$ , partial  $\eta^2 = .85$ . Mean values show that, overall, decision bias was less stringent (i.e. higher *c* values) for the 1600-standard time interval ( $M = -.301$ ) than for the 400-standard time interval ( $M = -1.204$ ). A significant effect was found for Time Increment Level,  $F(4, 104) = 158.618, p < .05$ , partial  $\eta^2 = .86$ . Not surprisingly, decision bias became less stringent (e.g.  $M_{TI-1} = -1.193$ ;  $M_{TI-3} = -.155$ ), as the time increment level increased. That is, increased saliency means less strict criteria needed to respond to a stimulus (See Figure 17).

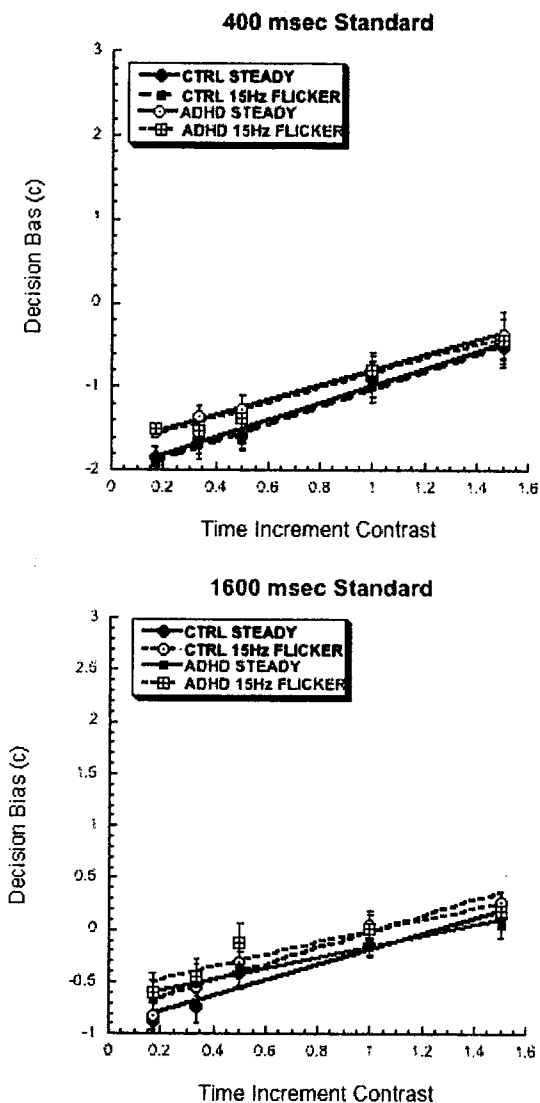


Figure 17. Control and ADHD-total group Decision Bias (*c*) as a function of Time Increment Contrast for both 400- and 1600-STI. Plots depict the difference in strictness between the two stimulus durations with the higher criterion values for the 1600 ms standard time interval indicating the application of a less strict decision strategy. This was true for both the Control (blue) and ADHD (red) groups. NFLK (FLK) data are shown with continuous (stippled) lines. Error bars represent  $\pm 1$  SEM.



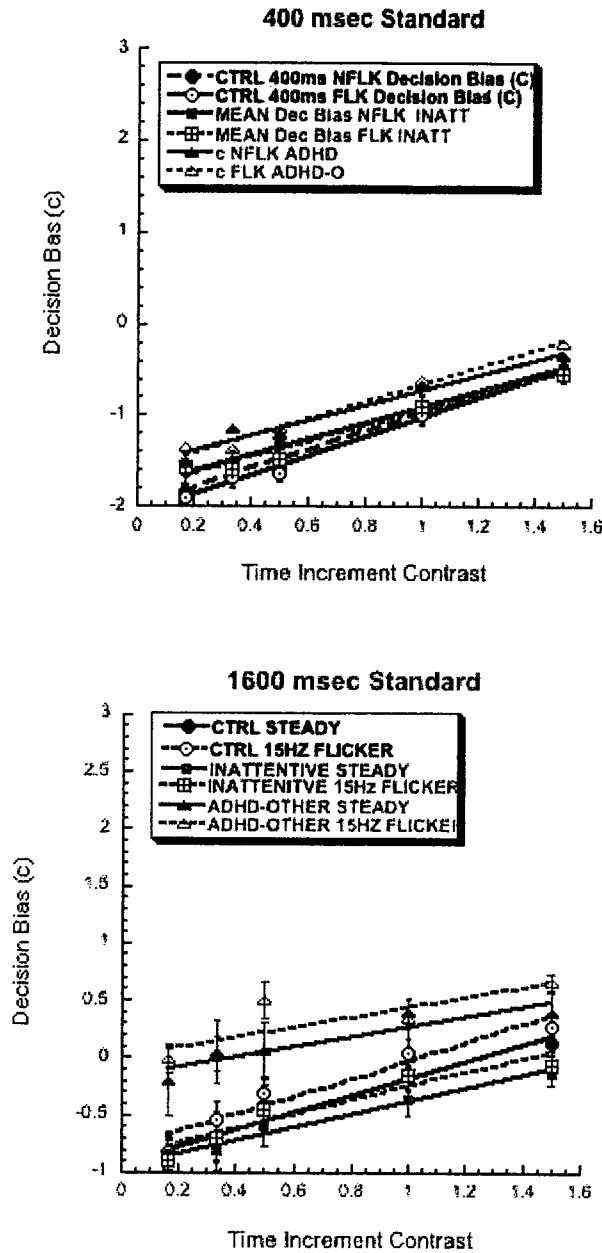


Figure 18. Decision bias (c) for Control (blue), Inattentive groups (red) and, ADHD-Other (green) as a function of Time Increment Contrast for both 400- (upper panel) and 1600-STI (lower panel). The ADHD-Other group applied a significantly less strict style of decision to 1600-STI than Control and Inattentive groups. NFLK (FLK) data are shown with continuous (stippled) lines. Error bars represent  $\pm 1$  SEM.

No significant main effect was found for Group ( $F(1, 26) = .945$ ,  $p = \text{n.s.}$ ), nor was one found for Stimulus ( $F(1, 26) = 1.761$ ,  $p = \text{n.s.}$ ). Significant interactions of Duration and Stimulus,  $F(1, 26) = 8.896$ ,  $p < .05$  (Figure 19), partial  $\eta^2 = .26$  and, Duration and Time Increment Contrast,  $F(4, 104) = 15.827$ ,  $p < .05$ , partial  $\eta^2 = .38$  (Figure 20) were found. Interactions depict lower criterion overall for the 1600-STI compared to the 400-STI. While stringency is lower for the flicker condition for the 1600-STI, the opposite is true for the 400-STI. Detailed descriptions of these interactions accompany Figures 19-20.

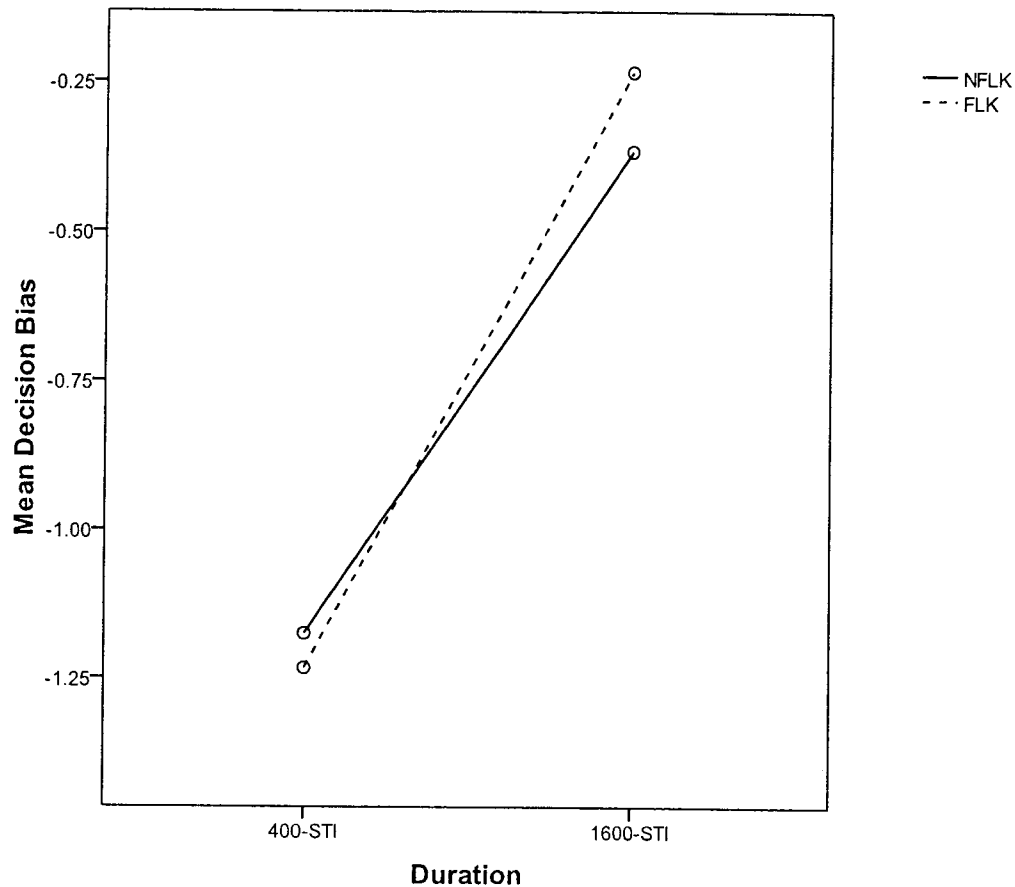


Figure 19. Mean decision bias (*c*) interactions between Duration and Stimulus (Control and ADHD-total groups combined). Decision bias was more strict for the 400-STI compared to 1600-STI. With respect to Stimulus, less strict criteria were found for 1600-STI FLK conditions which was opposite that found with 400-STI. In this case, NFLK produced more lenient criteria. NFLK (FLK) data are shown with continuous (stippled) lines.

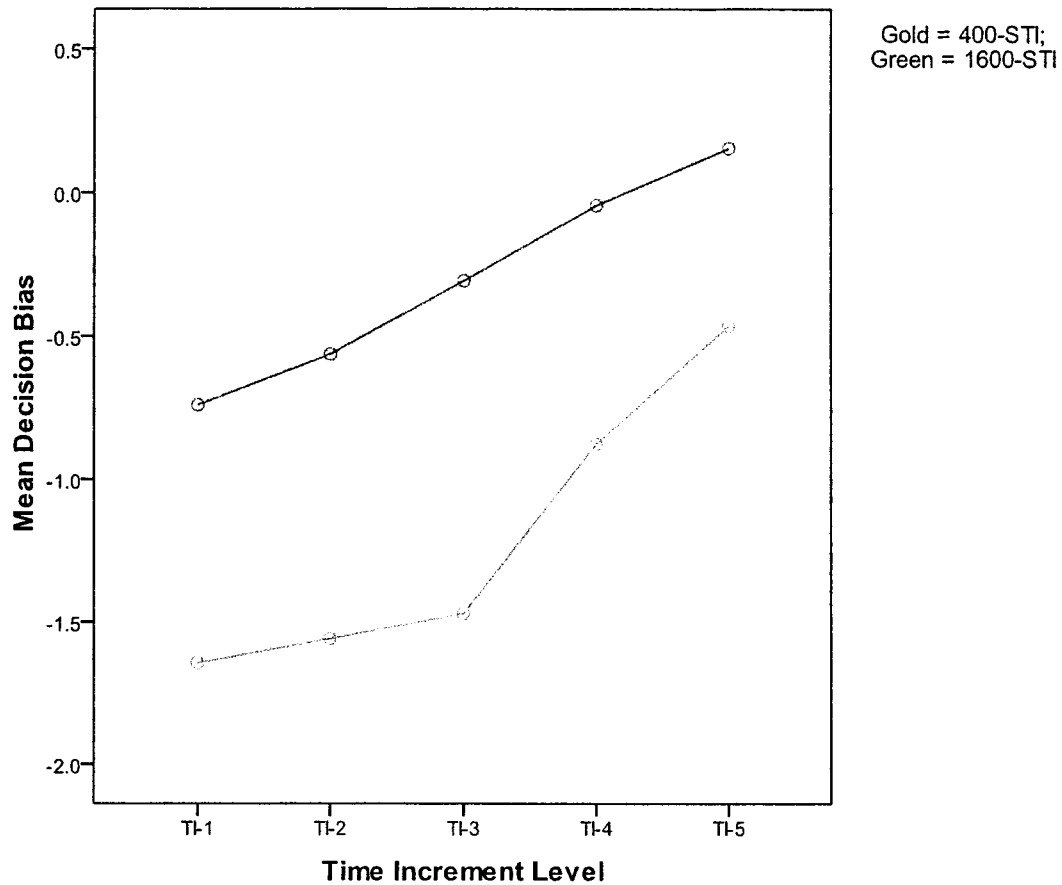


Figure 20. Mean decision bias (*c*) interactions between Time Increment Level and Duration (Control and ADHD-total groups combined). Decision bias is significantly higher for 1600-STI (green) across all time increments. Again, criterion becomes less strict as time increment level increases for both standard time intervals (see Fig. 4 caption).

To determine if differences in symptom presentation between ADHD subtypes (see section entitled Symptomology) is reflected in criterion stringency, an additional four factor 3 (Group) x 2 (Duration) x 2 (Stimulus) x 5 (Time Increment) repeated measures ANOVA was conducted with Group as the between-subjects factor. The three levels of Group include Control, ADHD-Other, and Inattentive. Analysis revealed a significant effect of Group,  $F(1, 25) = 3.504, p < .05, \text{partial } \eta^2 = .22$ . Post hoc multiple comparisons were performed using the LSD test. Criterion was significantly less strict for the ADHD-Other group ( $M = -.368$ ) than for both the Control group ( $M = -.817$ ) and the Inattentive group ( $M = -.846$ ). Analysis also revealed a significant effect of Duration on  $c$ ,  $F(1, 25) = 139.463, p < .05, \text{partial } \eta^2 = .85$ . Mean values show that, overall, decision bias was less stringent (i.e. higher  $c$  values) for the 1600-standard time interval ( $M = -.207$ ) than for the 400-standard time interval ( $M = -1.147$ ; See Figure 18). A significant effect was found for Time Increment Contrast. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom  $F(2.568, 100) = 105.425, p < .05, \text{partial } \eta^2 = .81$ . Stringency decreases significantly as the time increment contrast increases. A one-way ANOVA and post hoc LSD tests revealed that stringency was significantly lower for ADHD-other compared to both Control and Inattentive in responding to trials of the 400-STI FLK TI-1 ( $F(2, 25) = 7.023, p < .05$ ); 1600-STI NFLK TI-2 ( $F(2, 25) = 3.428, p < .05$ ); 1600-STI NFLK TI-4 ( $F(2, 25) = 4.477, p < .05$ ); 1600-STI FLK TI-1 ( $F(2, 25) = 4.415, p < .05$ ); and, the 1600-STI FLK TI-3 ( $F(2, 25) = 5.257, p < .05$ ). Criterion was higher for ADHD-other than for Control for the 400-STI FLK TI-3 ( $F(2, 25) = 3.568, p < .05$ ). Control and

ADHD-Other both applied less strict decision criteria than did Inattentive for trials of 1600-STI FLK TI-5 ( $F(2, 25) = 6.090, p < .05$ ).

No significant main effect was found for Stimulus ( $F(1, 22) = .120, p = \text{n.s.}$ ). Significant interactions of Duration and Stimulus,  $F(1, 25) = 5.406, p < .05$ , partial  $\eta^2 = .18$  (Figure 21) and Duration and Time Increment Contrast,  $F(3.538, 88.453) = 13.11, p < .05$ , partial  $\eta^2 = .31$  (Figure 22) were found.

Interactions show that criterion strictness decreases across time increments for both standard intervals and that criterion strictness is generally lower for the 1600-STI compared to the 400-STI. Furthermore, while no effect of stimulus on criteria were seen for the 400-STI, criterion was found to be less strict in the flicker condition for the 1600-STI. Detailed descriptions of these interactions accompany the figures below.

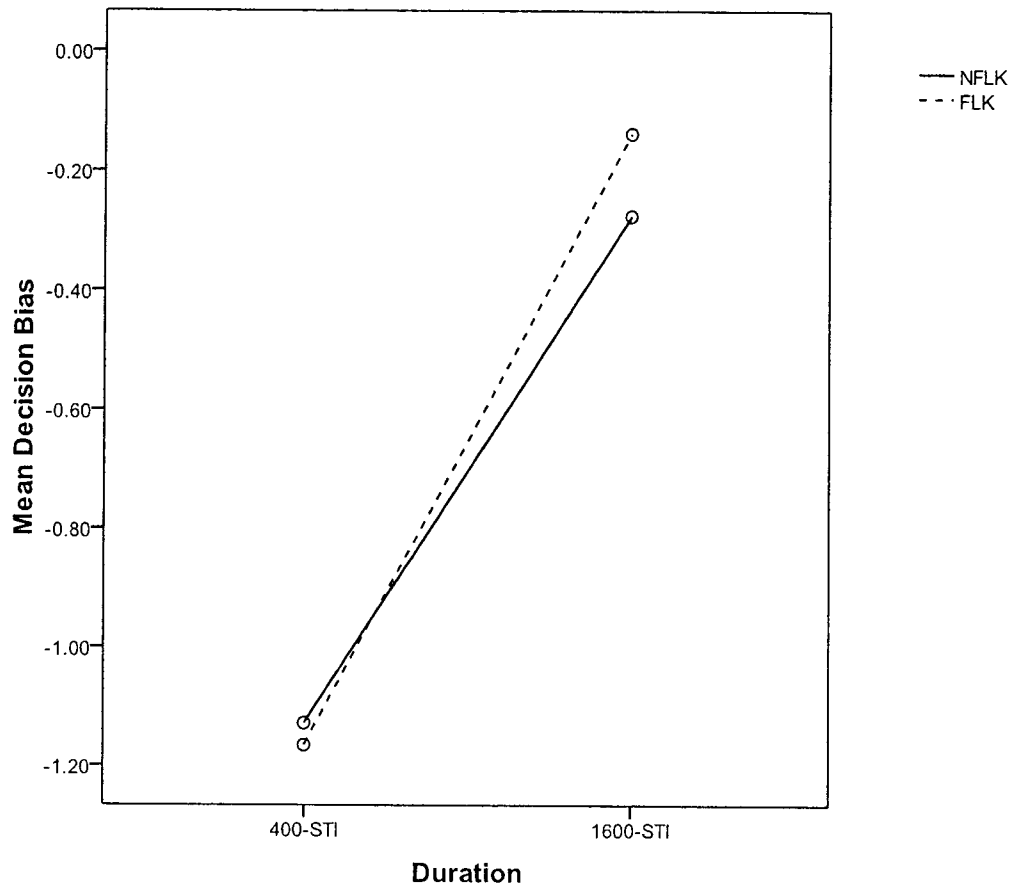


Figure 21. Mean decision bias (*c*) interactions between Duration and Stimulus (Control, Inattentive and ADHD-Other groups combined). With 400-STI, decision bias was approximately equal for both NFLK (continuous line) and FLK (stippled line) conditions. With 1600-STI, decision bias was higher for the flickering stimulus.

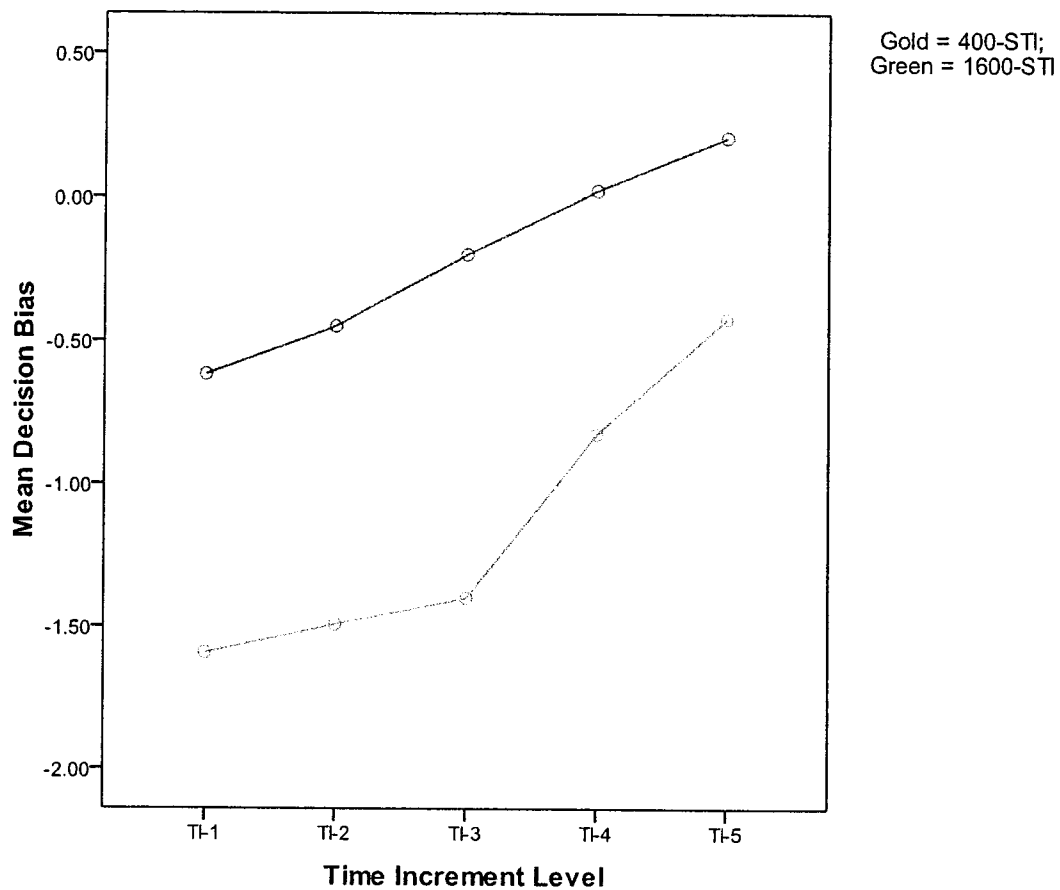


Figure 22. Mean decision bias ( $c$ ) interactions between Time Increment Level and Duration (Control, Inattentive and ADHD-Other groups, combined). Note the common trend: decision criteria became more lenient with increases in time increment levels, i.e. with increases in saliency. (see Fig. 3 caption). Decision bias was significantly higher with 1600-STI.



**Slope (Efficiency).** A three factor 2 (Group) x 2 (Duration) x 2 (Stimulus) repeated measures ANOVA was used to determine Group differences in slope. Group was the between-subjects factor. The two levels of Group include Control and ADHD-Total. Analysis revealed a significant effect of Group,  $F(1, 26) = 6.950$ ,  $p < .05$ , partial  $\eta^2 = .21$ . A post hoc one-way ANOVA revealed that slope was significantly higher for Control ( $M = 3.638$ ) than for ADHD-total ( $M = 1.814$ ) in the 400-STI NFLK condition ( $F(1, 26) = 8.316$ ,  $p < .05$ ). Analysis also revealed a significant effect of Duration,  $F(1, 26) = 33.107$ ,  $p < .05$ , partial  $\eta^2 = .56$ . Mean values show that, overall, slope was higher for the 400-standard time interval ( $M = 2.735$ ) than for the 1600-standard time interval ( $M = 1.216$ ).

Three factor.

A three factor 3 (Group) x 2 (Duration) x 2 (Stimulus) repeated measures ANOVA was used to determine Group differences in slope based on symptomology. Group was the between-subjects factor. The three levels of Group include Control, ADHD-Other and Inattentive. Analysis revealed a significant effect of Group,  $F(1, 25) = 4.476$ ,  $p < .05$ , partial  $\eta^2 = .26$ . A post hoc one-way ANOVA revealed that slope was significantly higher for Control ( $M = 3.638$ ) than for ADHD-total ( $M = 1.399$ ) and Inattentive ( $M = 2.022$ ) in the 400-STI NFLK condition ( $F(2, 25) = 4.241$ ,  $p < .05$ ). Analysis also revealed a significant effect of Duration,  $F(1, 25) = 18.261$ ,  $p < .05$ , partial  $\eta^2 = .42$ . Mean values show that, overall, slope was higher for the 400-standard time interval ( $M = 2.436$ ) than for the 1600-standard time interval ( $M = 1.112$ ). The interpolated average slopes are shown in Figure 23.

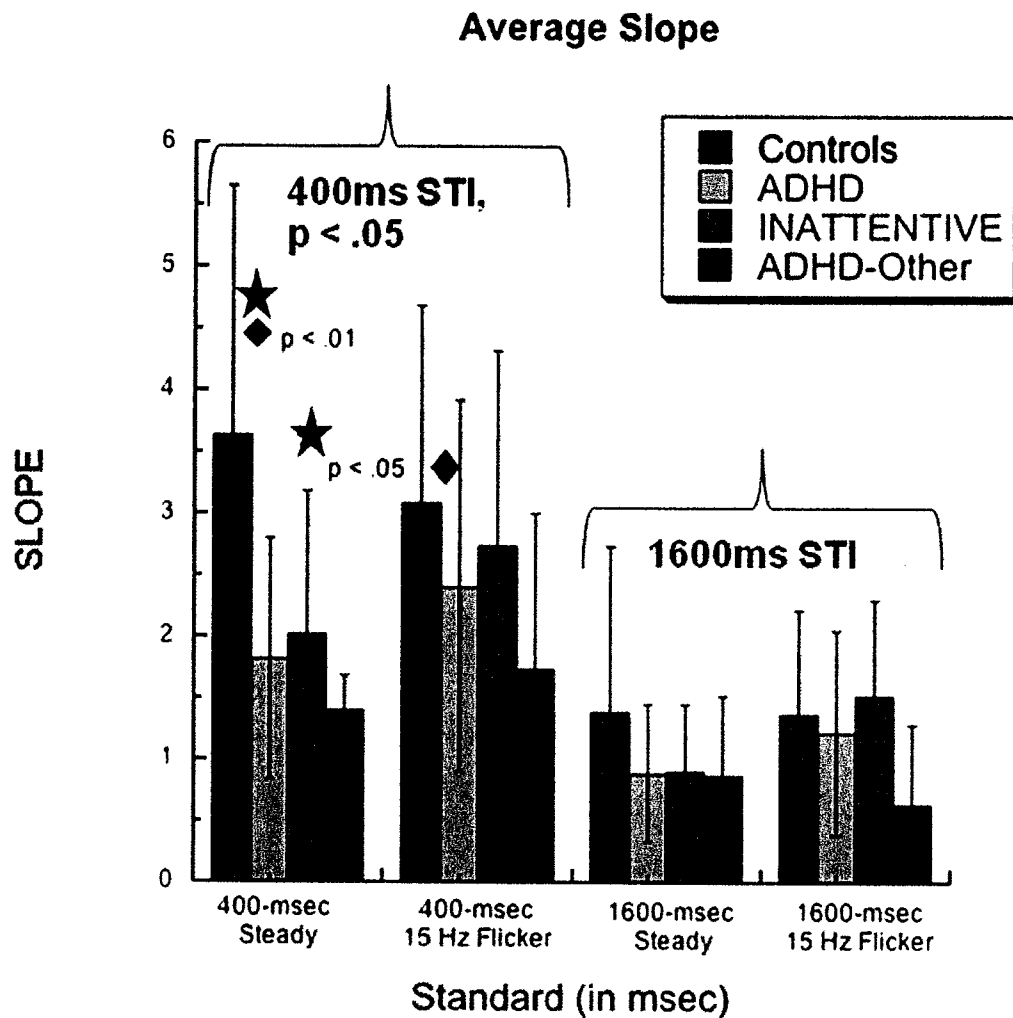


Figure 23. Slope means for all standard time interval and stimulus conditions. Higher slope is indicative of higher efficiency; Controls were found to be significantly more efficient than ADHD-total, Inattentive and ADHD-Other Groups with the 400-STI NFLK conditions. Although not significant, the Controls did consistently show greater efficiency than the ADHD Groups with the other conditions as well. Slope was found to be higher for the 400-STI compared to the 1600-STI for both stimulus conditions. Error bars are 95-percent Confidence Intervals. Asterisks denote significant differences between Control group and ADHD-total group at  $p < .01$ . The diamonds denote significant differences between Control and both the ADHD-other and Inattentive groups at  $p < .05$ .

**Threshold.** A three factor 2 (Group) x 2 (Duration) x 2 (Stimulus) repeated measures ANOVA was used to determine Group differences in threshold. Group was the between-subjects factor. The two levels of Group include Control and ADHD-Total. Analysis revealed a significant effect of Duration. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom  $F(1, 26) = 117.16$ ,  $p < .05$ , partial  $\eta^2 = .82$ . Mean values show that, overall, threshold was higher for the 400-standard time interval ( $M = 1.029$ ) than for the 1600-standard time interval ( $M = .448$ ). No significant effects of Group,  $F(1, 26) = .389$ ,  $p = \text{n.s.}$ , or Stimulus  $F(1, 26) = 1.507$ ,  $p = \text{n.s.}$  were found.

A three factor 3 (Group) x 2 (Duration) x 2 (Stimulus) repeated measures ANOVA was used to determine Group differences in threshold based symptomology. Group was the between-subjects factor. The three levels of Group include Control, ADHD-Other and Inattentive. Analysis revealed a significant effect of Duration. As the assumption of sphericity was violated, the Huynh-Feldt correction was used to correct the degrees of freedom  $F(1, 25) = 90.232$ ,  $p < .05$ , partial  $\eta^2 = .78$ . Mean values show that, overall, threshold was higher for the 400-standard time interval ( $M = 1.013$ ) than for the 1600-standard time interval ( $M = .413$ ). No significant effects of Group,  $F(1, 25) = 2.856$ ,  $p = \text{n.s.}$ , or Stimulus  $F(1, 25) = 1.162$ ,  $p = \text{n.s.}$  were found. The interpolated average thresholds are shown in Figure 24.

Significant interactions of Duration and Stimulus were found for Control and ADHD-Total,  $F(1, 26) = 9.759$ ,  $p < .05$ , partial  $\eta^2 = .27$  and for Control, ADHD-Other and Inattentive  $F(1, 25) = 4.365$ ,  $p < .05$ , partial  $\eta^2 = .15$ . (See Figures 25 and 26, respectively). Overall, interactions show the increased effect of flicker on improving

sensitivity for the 1600-STI compared to the 400-STI. These findings suggest that flicker entrainment has little effect on sensitivity for the 400-STI.

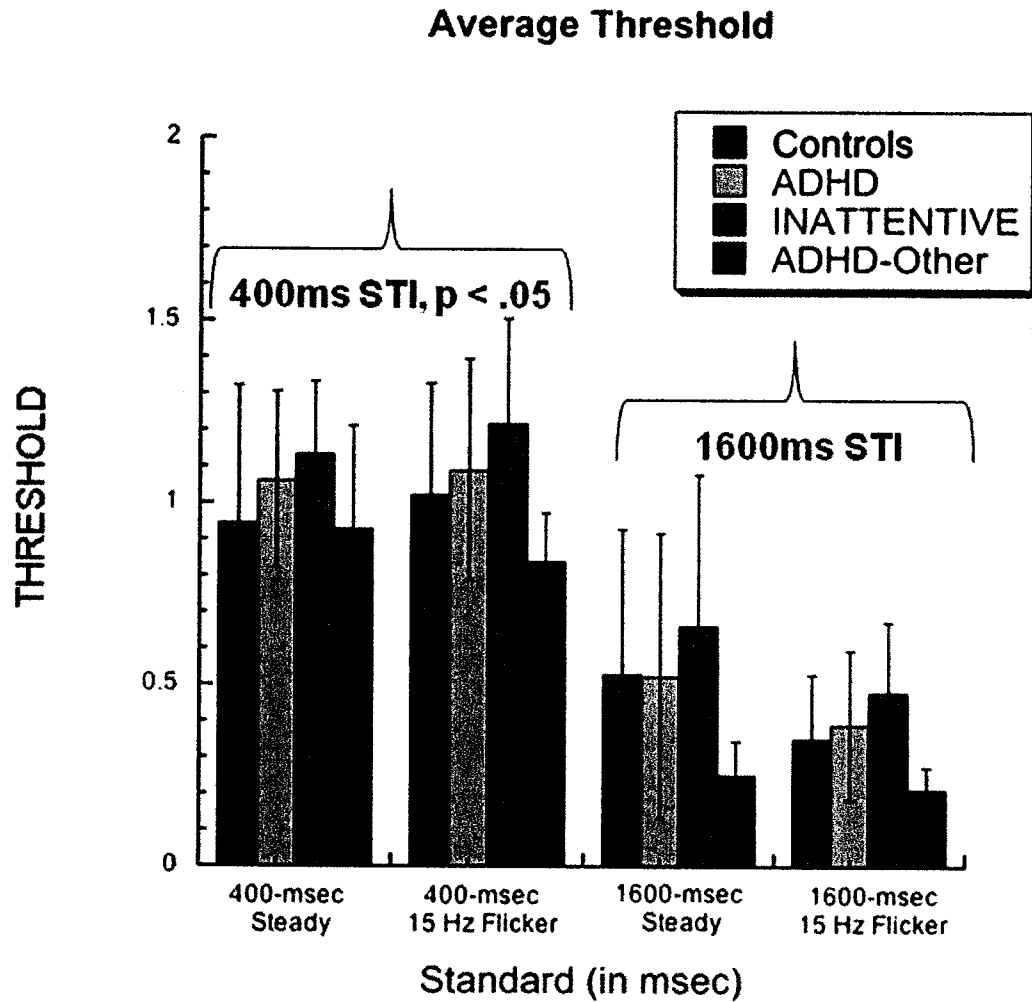


Figure 24. Threshold means for all standard time interval and stimulus conditions. Higher threshold is indicative of lower sensitivity. Threshold was found to be significantly higher for the 400-STI compared to the 1600-STI. Error bars are 95-percent Confidence Intervals.

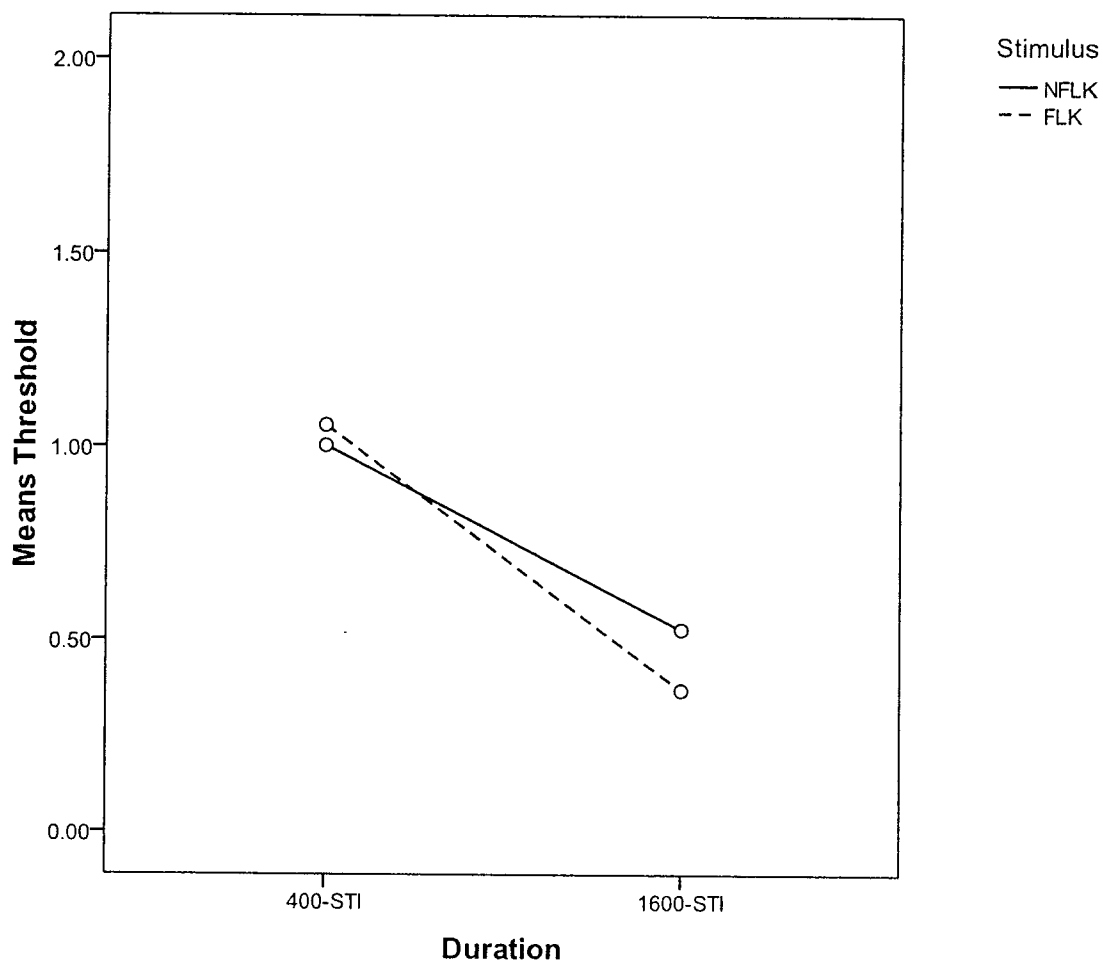


Figure 25. Threshold interaction effects between Duration and Stimulus (Control and ADHD-Total groups combined). NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Note that the flicker stimulus condition lowers threshold (i.e. increases sensitivity) for the 1600-STI (see Section Duration Discrimination and compared to the 400-STI).

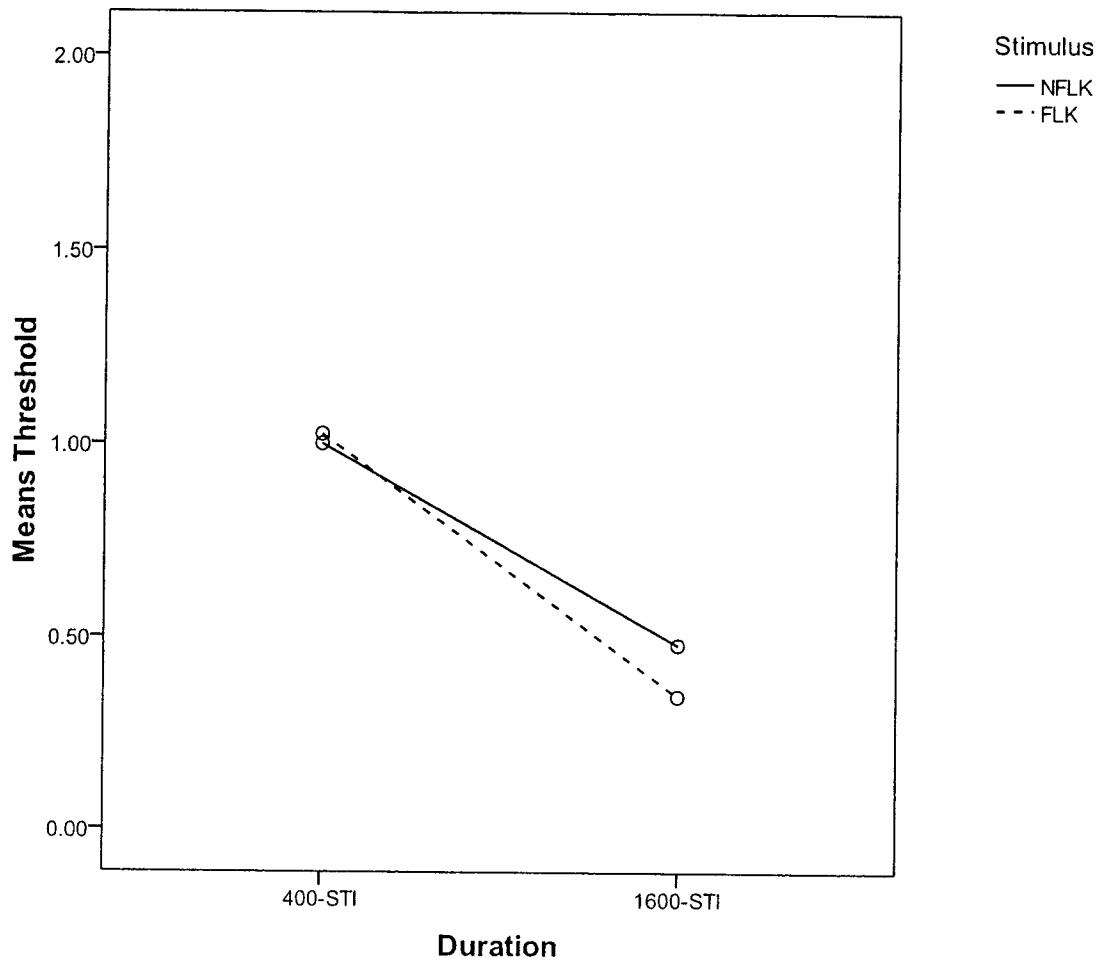


Figure 26. Threshold interaction effects between Duration and Stimulus (Control, ADHD-Other and Inattentive groups combined). NFLK (FLK) stimulus presentations are shown as continuous (stippled) lines. Again, the flicker stimulus condition lowers threshold (i.e. increases sensitivity) for the 1600-STI (see Section Duration Discrimination and compared to the 400-STI).

**Working Memory.** Results from a one-way ANOVA showed no significant differences in the WAIS-III working memory measures between Control and ADHD-total ( $F(1, 26) = .736, p = \text{n.s.}$ ). No significant differences between means of working memory for Control, Inattentive and ADHD-other were revealed by a second one-way ANOVA ( $F(2, 25) = 1.252, p = \text{n.s.}$ ).

Although no group differences were found, Pearson's correlation was used to determine the strength and direction of any existing relationships between working memory and accuracy, discriminability, criterion, slope and/or threshold. Significant positive correlations were found between working memory and proportion correct for the 1600-STI FLK TI-5 ( $r(26) = .391, p < .05$ ). Significant positive correlations were also found between working memory and discriminability for the following time increment levels: 400-STI NFLK TI-3 ( $r(26) = .384, p < .05$ ); 400-STI FLK TI-4 ( $r(26) = .409, p < .05$ ); 400-STI FLK TI-5 ( $r(26) = .392, p < .05$ ); 1600-STI NFLK TI-2 ( $r(26) = .392, p < .05$ ); 1600-STI NFLK TI-4 ( $r(26) = .381, p < .05$ ); 1600-STI FLK TI-1 ( $r(26) = .463, p < .05$ ); 1600-STI FLK TI-3 ( $r(26) = .377, p < .05$ ); and, 1600-STI FLK TI-5 ( $r(26) = .393, p < .05$ ). A significant negative correlation was found between working memory and threshold for the 400-STI FLK condition ( $r(26) = -.393, p < .05$ ). These results indicate that cognitive factors are involved in temporal processing. Specifically, better working memory performance is correlated with higher accuracy for durations greater than one second at suprathreshold levels. Furthermore, higher working memory scores are correlated with better discriminability performance at suprathreshold levels for the 400-STI, irrespective of stimulus condition. With respect to the 1600-STI, as working memory scores increase, so does discriminability in both non-flicker and flicker



conditions. In particular, working memory scores do seem to be related to improved subthreshold performance for the 1600-STI. Finally, results indicate that as working memory scores increase, 50-percent threshold decreases.

## Discussion

### Non-ADHD Adults and ADHD Adults

Overall, results of the present study demonstrate differences in temporal processing and time perception between non-ADHD and ADHD adults. Comprised of both sensory ( $d'$ ) and cognitive ( $c$ ) components, the accuracy (i.e., proportion correct) of responding is an overall indication of performance on duration discrimination tasks such as the one executed by all groups in this study (Ciaramitaro et al., 2001). Given the relationship between discriminability, criterion and proportion correct, it is impossible to discuss accuracy without referring to its sensory and cognitive components. As such, mention of findings related to discriminability and criterion is included in the discussion of proportion correct.

Differences in accuracy between non-ADHD and ADHD-total adults were assessed. A significant main effect of Duration was found where accuracy was found to be significantly higher with 1600-STI versus 400-STI presentations. There were also significant interaction differences between Controls and ADHD-total groups with respect to specific time increment levels. In particular, non-ADHD adults were more accurate than ADHD adults with the 1600-STI FLK TI-5 (*a supra-threshold level*), ADHD adults, however, were more accurate with 400-STI FLK TI-1 (*a sub-threshold level*). Although the difference between groups for the 400-STI FLK TI-1 is difficult to decipher, the difference between groups for the 1600-STI FLK TI-5 is apparent with the fitted Weibull

curves depicted in Fig. 1. The fitted curves depict greater accuracy with the Control group at the supra-threshold levels. As there was no significant effect of Stimulus, flicker entrainment likely did not contribute to the higher accuracy score obtained by the ADHD-total adults for the 400-STI FLK TI-1 level. Instead, the significantly less strict responding (a cognitive strategy; see Decision Bias section above) of the ADHD-other group may have overshadowed any contribution by the Inattentive group to this result, accounting for the difference between Controls and ADHD-total groups at 400-STI FLK TI-1. If true, the application of a less strict decisional strategy might be considered a compensatory mechanism for a sensory deficit on the part of the ADHD-other group.

Significant differences were also found between these two groups in their ability to discriminate time increment contrasts. In particular, non-ADHD adults were better able to discriminate time increment contrasts for the 1600 standard time interval than were ADHD adults (see Figure 8). This finding is in agreement with findings by several researchers, including Toplack and Tannock (2005), who demonstrated deficits in high-end component operations in ADHD adolescents compared to controls. In obtaining these results, we have demonstrated that these deficits persist into adulthood. We have also provided support of previous findings of high-end temporal processing deficits (i.e., effects are evident when durations are greater than 1 second mark) on the part of ADHD adults (see Barkley et al. 2001).

Two significant interactions associated with PC for non-ADHD and ADHD-total adults were found. In the first (Duration x Stimulus, as shown in Fig.3), flickering the stimulus appears to have the most effect on improving accuracy for the 1600ms standard interval. Decision bias was also higher for 1600-STI, FLK condition (See Figure 19). For the 400 ms standard interval, however, proportion correct is greater for the non-

flicker stimulus condition. Flicker entrainment has been implicated in improving resolution for discrimination of intervals greater than one second while no such effect has been found for discrimination of intervals below one second (e.g., Wesner & Prenger, 2005). Wesner and Prenger suggest that durations of 400 ms were too short an epoch to distinguish temporal resolution, while Driot-Volet and Wearden (2002) found that increasing pacemaker speed (see p. 22 of the present study) subjectively shortened durations. If the latter is true, the subjective shortening of duration may indeed lead to what Wesner and Prenger suggest – difficulty isolating 400-ms durations that are perceived to be even shorter in duration. As mentioned earlier, evidence of one system for low-end component operations in timing and another for high-end component operations has been presented (e.g., Wesner & Prenger, 2005). At the very least, despite the entrainment effects tied to the longer 1600-STI, our findings *do* provide support for a two-component system of temporal processing. The second interaction (Duration x Time Increment Level, Figure 4) reveals a large difference in accuracy between 400- and 1600-STI at the small time increment contrast levels while at the large levels accuracy for both standard intervals is equal. In this interaction, accuracy for the 1600 ms standard interval increases at a steady and consistent rate while accuracy for the 400 ms standard interval increases gradually at the smaller time increment levels and then rapidly increases at the middle (TI=3) increment. This pattern is similar to that of the effects of Duration and Time Increment Contrast on discriminability (a sensory process) for these two groups (Figure 12). As such, this effect does not seem to be dependent on only sensory mechanisms. An interaction between Duration and Time Increment Level was also associated with Decision Bias (See Figure 20). Criterion (*c*) was shown to be less strict with 1600-STI than 400-STI, which may help to explain the higher PC (accuracy) for the

1600-STI (i.e. more lenient pattern of responding increases likelihood of a correct response). Another explanation for these findings is the one provided by Wesner & Prenger mentioned above: durations of 400 ms are too short to distinguish with consistent accuracy.

Three significant interactions were found with discriminability ( $d'$ ) for non-ADHD and ADHD adults. The first of these (Group x Time Increment Level; see Figure 9) reveals that the non-ADHD adults and the ADHD-total adults were almost identical with respect to discrimination performance at the smaller time increment levels. At the higher end, however, non-ADHD adults performed significantly better than did the ADHD adults. This effect is demonstrated in Figure 8, where fitted Weibull curves for the 1600-ms standard time interval are clustered together at the smaller time increment contrasts and separate according to group as time increment contrasts increase to supra-threshold levels. A possible explanation for this is the existence of two operating systems for the processing and perception of time. Evidence supports the involvement of cognitive factors such as attention in the temporal processing of intervals greater than one second (e.g. Lewis & Miall, 2003; Rammsayer & Lima, 1991). Considering the cognitive deficits associated with ADHD (e.g. Johnson et al., 2001), one would expect, then, for ADHD adults to perform less well with durations longer than 1000 msec.

The fact that a greater Group separation occurred with  $d'$  rather than with PC suggests that adult ADHD dysfunction is associated more with sensory components than with cognitive decision making components. This last statement is confirmed by the fact that outside of the expected rise in  $c$  with increased time contrast increments, there was little separation between ADHD-total and Control groups.

A second interaction (Duration x Stimulus; see Figure 10) suggests that flickering the circular stimulus (FLK) enhances discrimination performance most notably with 1600-STI. No such effect was found with 400-STI. This effect can be seen in Figure 8 where, for both groups, fitted curves for the flicker stimulus extend upward beyond the non-flicker curves. Again, a two-component timing system for the processing and perception of time may explain these findings. It is possible our findings may be the result of attentional allocation; at the low end, attentional resources are not called upon due to the speed of the temporal event, whereas the opposite is true at the high-end operations which may be invoked by 1600 ms standard presentations. Again, findings of Wesner and Prenger (see above) may serve to explain the interaction of duration and flicker for the non-ADHD and ADHD adult group. That is, for these non-ADHD and ADHD adults, the flicker stimulus serves to increase pacemaker speed, regardless of clinical-based overall deficiencies. A third interaction (Duration x Time Increment Level, see Figure 12) simply demonstrates the increase in discrimination performance as time increment level increases. An interesting thing to note is the consistent increase in discriminability with 1600-STI across all time increments while with 400-STI, discriminability increases gradually at the smaller time increments and rises quite quickly at the higher time increments—the elbow of the function usually occurring around TI-3. These respective gradual and sharp rises in discriminability can be seen the fitted Weibull functions shown in Figure 8. As Wesner and Prenger speculate, this could be due an inability to distinguish differences in time increment at the smallest contrasts for the 400-ms standard time interval while longer durations that allow for top-down resource allocation can make appropriate adjustments to duration changes.

A review of temporal processing research that compares experimental ADHD participants to that of Control rarely considers potential differences in performance based on ADHD subtypes. Research conducted outside of the temporal processing field (e.g. strictly clinical research; developmental studies) that involves ADHD participants as experimental groups do, however, examine differences between ADHD subtypes. For example, one experiment conducted by Derefinko et al. (2008) does provide some insight into our findings. Derefinko et al. examined the response of a Comparison (control) group, an ADHD/Combined group and an ADHD/Inattentive group styles on an inhibitory behavioural task. Participants were children (9-12 years); those who made up the ADHD groups were formally diagnosed. All children participated in a reaction time task and a “go”/“no go” task. In the reaction time task, a fixation point was presented on a computer screen for 800 ms. After a 500 ms inter-stimulus-interval, a “go” cue or a “no go” cue was presented, followed by a target stimulus either 100, 200, 300, 400 or 500 ms later. If the cue was “go”, the participant was instructed to press a button when the target stimulus appeared (green); if the cue was “no go”, the participant was instructed to inhibit their response when the target stimulus appeared (blue). If a “go” cue was followed by a blue target stimulus, participants were required to inhibit their response and vice versa for a “no go” cue followed by a green target stimulus. According to Derefinko et al., when a “go” cue is followed by a “no go (blue)” target, the participant is primed to make a “go” response. As a result, the participant is more likely to respond incorrectly to the “no go” target (i.e., commits an “inhibitory failure”). As a result of these failures, it was expected that significantly more errors would be committed on the “go” trials than the “no-go” trials. Findings of the study reveal that this was true of both the Comparison and ADHD/Combined, who made the same number of inhibitory errors across “go” and “no

go” trials. The ADHD/Inattentive group also had slower reaction times than the other groups following go and no-go cues. In the second task, participants were required to learn, according to feedback, when to respond to a stimulus (double digit numbers displayed on a computer screen) and when to inhibit responding. For correct responses participants received five cents; for incorrect responses, participants lost five cents. Results of this task show that the ADHD/Inattentive group made more errors of omission and had slower and more variable response times than the Comparison and ADHD/Combined groups, who were not different from each other. Derefinko et al. referred to this response style as a “sluggish cognitive tempo”, marked by slow responding with poor performance and consistent inattention. As this response style was consistent across different tasks, the authors contended that this style of responding was inherent to the ADHD-Inattentive subtype. Because of the apparent uniqueness of this ADHD subtype, we further investigated performance differences between ADHD subtypes, where we divided the ADHD group into adult ADHD-other participants (those with symptoms consistent with the Hyperactive/Impulsive or Combined) and Inattentive participants (those with symptoms consistent with the Inattentive subtype).

Comparisons of PC between non-ADHD adults, Inattentive and ADHD-Other adults revealed significant difference in accuracy. It was found that PC was higher with 1600-STI than with 400-STI. More specifically, overall ADHD-Other adults were more accurate with the longer standard interval at sub-threshold levels, compared to Control and Inattentive adults. The Control group, however, was more accurate than the Inattentive group with the 1600-STI at the supra-threshold levels. Psychometric functions clearly demonstrate these findings in Figure 2 with the crossing over of fitted functions from sub- to supra-threshold time increment contrast values. The ADHD-Other

groups also applied a less strict criterion with 1600-STI at sub-threshold levels, which may explain that group's increased accuracy. Both Control and ADHD-Other were less strict than the Inattentive group at the supra-threshold level, again providing some explanation for better accuracy on the part of the Control and ADHD-Other groups. Ciaramitaro et al offer evidence that prior knowledge about the characteristics of a stimulus change an individual's decision process. As a result, any change in performance is attributable to a change in cognitive processing and not to a change in sensory processing.

Three significant interactions associated with proportion correct for non-ADHD, Inattentive and ADHD-Other adults were found. The first (Group x Duration, as seen in Figure 5) demonstrates the greater accuracy on the part of the ADHD-Other group compared to the Control and Inattentive groups, as well as greater accuracy with 1600-STI for Control compared to Inattentive. The second interaction (Duration x Stimulus, see Figure 6) is similar to the interaction between Duration and Stimulus described previously. Flickering the stimulus had the greatest effect on improving accuracy with 1600-STI. With 400-STI, however, proportion correct was greater with the NFLK condition. An interaction between Duration and Stimulus (see Figure 21) associated with Decision Bias shows that criterion was least strict with 1600-STI, FLK and most strict with 400-STI, FLK, which may serve to partially explain the differences between these three groups described above. A third interaction (Duration x Time Increment Level, See Figure 7) reveals large differences in accuracy between the 400 ms standard time interval and the 1600 ms standard time interval conditions. Difficulties in distinguishing temporal events within the 400-STI epoch may explain these patterns (i.e., Wesner & Prenger, 2005). PC (accuracy) was higher with 1600-STI at small time increment levels



while at large time increment levels, accuracy for both standard intervals was equal. With respect to decision bias, an interaction of Duration x Time Increment Level (see Fig. 22) shows a significantly higher criterion with 1600-STI compared to 400-STI, which could have contributed to the higher accuracy reported with the 1600-STI condition.

In the present study, non-ADHD adults were found to discriminate small differences in duration significantly better than both the Inattentive and ADHD-Other adults. Overall, non-ADHD adults were better able to discriminate time increment contrast with 1600-ms standards than all ADHD Groups. This difference is clearly depicted by the transducer function in Figure 9. The increase in discriminability as time increment contrast increases is depicted for all groups, as is the gradual increase in discriminability performance separation found between Control, Inattentive and ADHD-Other groups, with the most marked separations occurring at high-end 1600-STI operations (*cf.* upper panel versus lower panel).

Three significant interactions for discriminability were identified. In the first interaction (Group x Stimulus x Time Increment Level), Figures 13 and 14 show an interesting pattern of discriminability. In the NFLK condition, the ADHD-Other group performs relatively better overall for the smaller time increments (TI-2), while with FLK, the same group performs relatively better for the larger increments (TI-5). It is possible that at sub-threshold levels below 0.5 PC, flicker entrainment has no effect on this group due to non-modulatory lower-end sensory deficit while at longer durations cognitive factors contribute to performance. Indeed, the ADHD-other group was found to engage in a more conservative decision making-strategy in responding to stimuli than both other groups, and for all groups decision-making was the most strict for the flicker condition. As such, it is likely that cognitive, rather than sensory, factors did contribute to the

increased performance of the ADHD-other group in the flicker condition. The performance pattern of the Inattentive group remains unchanged between stimulus conditions, suggesting that the presence of some overall insensitivity to entrainment, similar to the “sluggish” response pattern described by Derefinko et al (2008) establishes an impenetrable neural property that is incapable of top-down modulations with longer time increments, despite potential subject tactics designed to enhance timing performance.

In the second interaction (Duration x Stimulus, Figure 15) 15 Hz stimulus flicker seemed to increase the discriminability of the 1600-ms standard interval compared to the 400-ms standard interval for the Control, ADHD-Other and Inattentive groups.

In the third interaction, (Duration x Time Increment Level; Figure 16), discrimination performance increased steadily with 1600-STI while discrimination performance with 400-STI began gradually before it rose rapidly at TI-3, surpassing the discriminability of the 1600 ms standard. These findings suggest that, despite better overall discrimination performance with 1600-STI, at the largest time increment contrast, all groups found it easier to discriminate from a 400-ms standard time interval than from a 1600-ms standard time interval.

While the Control group was better able to discriminate small differences in duration for the 1600-STI, ADHD-other applied a less strict criterion. Results also show higher accuracy on the part of the ADHD-other group for the 1600 standard time interval. These findings suggest that despite applying a cognitive strategy, which enhanced accuracy, sensory  $d'$  discrimination did not improve. What this finding suggests is that while ADHD-other adults are able to apply decision-making strategies (i.e., cognitive

processes to carry out a perceptual tasks), these strategies are accompanied by some sensory deficit that inhibits improved perceptual performance.

It is most likely that both the Control and ADHD-other groups applied both cognitive and sensory resources to complete the tasks. Despite this, the Control group, without a concomitant sensory deficit, performed better than the ADHD-Other group. This points to a sensory-perceptual deficit that directly underlies the cognitive deficits experienced by the ADHD-Other group. As discrimination performance and criterion were significantly lower for the Inattentive group than both the Control and ADHD-other groups, it is difficult to know exactly how sensory and/or cognitive factors contributed to that group's performance. Evidence from the present study seems to support Derefinko et al.'s findings of overall "sluggish cognitive tempo" on the part of the ADHD-Inattentive subtype.

Slopes of the fitted functions were used to convey information about performance efficiency (i.e., the higher the slope, the more efficient the discrimination performance) (Macmillan & Creelman, 1991). Overall, slope was higher for the 400-STI compared to the 1600-STI. Figure 23 shows mean slope values for the Control group, the ADHD-total group, the Inattentive group and, the ADHD-Other group. The Control group was most efficient in correctly identifying differences in duration than all other groups with the 400-ms standard time interval, NFLK condition. It is possible that no differences in proportion correct were found between Control and ADHD-other due to a trade-off of accuracy in favour of efficiency. In any case, better discriminability, despite no differences in accuracy, point to a sensory deficit on the part of the ADHD-Other group.

Difference thresholds for each condition were estimated from an interpolated 50% correct measure, as derived from a Weibull psychometric function that was fit to the data

sets (e.g., MacMillan and Creelman, 1991). Means are depicted in Fig. 24. Overall, threshold was higher for the 400-STI compared to the 1600-STI. Furthermore, flicker was shown to enhance sensitivity for the 1600-STI compared to the 400-STI. No significant differences in threshold were found between Control and ADHD-total group, nor were any found between the Control, ADHD-other or Inattentive groups. The lack of any significant group differences in threshold is most likely due to group differences in discriminability and criterion. While the Control group was better able to discriminate changes in duration, the ADHD-other group applied a less strict criterion. As both these processes contribute to accuracy (from which threshold is derived), perhaps their relative effect on threshold was balanced out. In addition, fewer significant differences were found for the Inattentive group and as such, significant differences in threshold were unlikely.

The finding of no significant differences in working memory defined by our psychometric measurements for any two groups could be the result of many factors, one of which could be sample size. Importantly, we did find significant relationships between working memory and accuracy, discriminability and threshold for all groups, clearly implicating cognitive factors in temporal processing. Despite the lack of significant group differences, we *still* found evidence of a sensory deficit for the ADHD-other group and some indication of sensory deficits on the part of the Inattentive group. Perhaps this indicates that a focus on cognitive factors in investigating the pathology of those with ADHD is misplaced, or at the very least, warrants continued investigations using highly regimented experimental methodologies such as those established in our psychophysical methods.

## Conclusion

The present study investigated ADHD adults and their ability to process short (below 1000 ms) and long (above 1000 ms) temporal events. Although research has demonstrated time perception deficits in individuals with ADHD, up until now, most, if not all, of the research has been on ADHD children. Findings of the present study have demonstrated timing deficits on the part of ADHD adults for intervals greater than one second. Increase in performance due to flicker entrainment was apparent, particularly with respect to the 1600-STI and the ADHD-Other group. With respect to the effects of flicker on the performance on 400-STI it is possible that entrainment itself is duration-dependent, that is, a duration of 400 msec may not be long enough for entrainment to occur to the degree where its effects are observable. To assess this, researchers might consider measuring entrainment effects at several duration levels flanking the one second mark. Doing this would allow researchers to more specifically characterize the entrainment phenomenon. Certainly, our findings indicate that further research on this phenomenon and its relationship to ADHD subtypes is warranted. Evidence of a sensory deficit is evident both in the deficient discrimination performance compared to Controls and the non-responsiveness of the Inattentive group to flicker entrainment. If it is as Derefinko et al (2008) suggest, and Inattentive-type individuals experience some type of overall sensory lethargy, perhaps experiments investigating the Inattentive ADHD subtype should be designed with that in mind.

Our findings do not support previous findings of working memory deficits on the part of ADHD adults. Findings provided additional evidence of two timing systems – a low-end component operations system for intervals of less than one second and a high-end component operations system for intervals of greater than one second. Although

most duration effects demonstrated high-end processing differences across groups, we did obtain results that point to sensory-perceptual processing deficits on the part of individuals with ADHD Hyperactive/Impulsive and ADHD-Combined symptoms. In accomplishing this, our study is informative beyond the current understanding of ADHD that is derived from overt behavioural symptoms.

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## Appendix A

## Diagnosis of ADHD

Before a diagnosis of ADHD is made, the clinician must complete a thorough assessment. Typically, such an assessment includes collection of relevant information from several sources. These sources can include medical and school records, details about the child's home environment, medical and academic histories of parents, and observations made by teachers. This information is examined in conjunction with details of the child's behaviours. (NIMH, Diagnosis, para. 8, 9 & 10) If the accumulated information so indicates and if the child's behaviours meet the criteria for ADHD as listed in the DSM-IV-TR, a diagnosis of ADHD can be made. A DSM-IV-TR diagnosis of ADHD requires that following criteria be met:

## A) Either (1) or (2):

1. six (or more) of the following symptoms of **inattention** have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:
  - a. often fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities
  - b. often has difficulty sustaining attention in tasks or play activities
  - c. often does not seem to listen when spoken to directly
  - d. often does not follow through on instructions and fails to finish schoolwork, chores, or duties in the workplace (not due to oppositional behavior or failure to understand instructions)
  - e. often has difficulty organizing tasks and activities
  - f. often avoids, dislikes, or is reluctant to engage in tasks that require sustained mental effort (such as schoolwork or homework)
  - g. often loses things necessary for tasks or activities (e.g., toys, school assignments, pencils, books, or tools)

- h. is often easily distracted by extraneous stimuli
  - i. is often forgetful in daily activities
2. six (or more) of the following symptoms of **hyperactivity-impulsivity** have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:

*Hyperactivity*

- a. often fidgets with hands or feet or squirms in seat
- b. often leaves seat in classroom or in other situations in which remaining seated is expected
- c. often runs about or climbs excessively in situations in which it is inappropriate (in adolescents or adults, may be limited to subjective feelings of restlessness)
- d. often has difficulty playing or engaging in leisure activities quietly
- e. is often "on the go" or often acts as if "driven by a motor"
- f. often talks excessively

*Impulsivity*

- g. often blurts out answers before questions have been completed
  - h. often has difficulty awaiting turn
  - i. often interrupts or intrudes on others (e.g., butts into conversations or games)
- B. Some hyperactive-impulsive or inattentive symptoms that caused impairment were present before age 7 years.
- C. Some impairment from the symptoms is present in two or more settings (e.g., at school [or work] and at home).
- D. There must be clear evidence of clinically significant impairment in social, academic, or occupational functioning.
- E. The symptoms do not occur exclusively during the course of a Pervasive Developmental Disorder, Schizophrenia, or other Psychotic Disorder and are not



better accounted for by another mental disorder (e.g., Mood Disorder, Anxiety Disorder, Dissociative Disorder, or a Personality Disorder).

*Code based on type:*

- **Attention-Deficit/Hyperactivity Disorder, Combined Type:** if both Criteria A1 and A2 are met for the past 6 months.
- **Attention-Deficit/Hyperactivity Disorder, Predominantly Inattentive Type:** if Criterion A1 is met but Criterion A2 is not met for the past 6 months.
- **Attention-Deficit/Hyperactivity Disorder, Predominantly Hyperactive-Impulsive Type:** if Criterion A2 is met but Criterion A1 is not met for the past 6 months. (*DSM-IV-TR*, 2000, p.92-93)

## Appendix B

## Participant Demographic Information

<u>SUBJECT</u> <u>Number</u>	<u>CTRLs or</u> <u>ADHD-TYPE</u>	<u>GENDER</u>	<u>AGE</u>	<u>CORRECTIVE</u> <u>LENSES</u>	<u>EYE</u> <u>SURGERY</u>	<u>DAILY MEDICATION</u>
002	CTRL	F	19	Yes	No	No
003	CTRL	F	24	No	No	No
008	CTRL	F	21	Yes	No	No
010	CTRL	F	19	No	No	No
011	CTRL	M	21	No	No	No
013	CTRL	M	22	No	No	No
014	CTRL	F	18	Yes	No	Yes- Contraception
017	CTRL	F	18	No	No	Yes- Contraception; Antibiotic; Insulin
019	CTRL	M	20	No	No	No
023	CTRL	F	19	Yes	No	Yes- Contraception
025	CTRL	F	25	Yes	No	Yes- Anxiolytic
027	CTRL	M	24	Yes	No	No
028	CTRL	F	26	No	Yes	No
029	CTRL	F	25	Yes	No	No
030	CTRL	F	22	Yes	No	Yes- Anxiolytic
031	CTRL	F	39	Yes	No	No
033	CTRL	F	27	No	Yes	No
004	COMBINED	M	20	No	No	No
006	COMBINED	F	19	No	No	No
024	HYP/IMP	F	28	Yes	No	No
026	HYP/IMP	F	24	No	No	Y – Asthma medication; B12
005	INATTENTIVE	F	24	No	No	Yes- Contraception
007	INATTENTIVE	M	19	Yes	No	No
009	INATTENTIVE	M	27	No	No	No
012	INATTENTIVE	F	22	Yes	No	Yes- Contraception
015	INATTENTIVE	M	19	No	No	No
016	INATTENTIVE	M	20	No	No	No
020	INATTENTIVE	M	18	No	No	No
021	INATTENTIVE	M	20	No	No	No

Appendix C

Duration Discrimination Task

