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Abstract

This study compared inhibitory functioning among ADHD subtype groups on manual and visual versions of the stop task. Seventy-six children, identified as ADHD/I ($n = 16$), ADHD/C ($n = 42$), and comparison ($n = 18$) completed both tasks. Results indicated that both ADHD groups were slower to inhibit responses than the comparison group on both tasks. Comparison children were faster to inhibit than activate responses on both versions of the task. Children in the ADHD groups also demonstrated this robust pattern on the manual task. However, on the visual task, children in the ADHD groups evidenced slowed inhibition comparable to the time required to activate responding. This implies that the visual task is more sensitive to inhibitory impairment in ADHD than the manual task. The ADHD/I group did not differ from children with ADHD/C on most measures, suggesting that the stop task is not effective in differentiating the subtypes. These findings extend work highlighting the role of disinhibition in ADHD, and contrast recent work suggesting divergence between ADHD subtypes.

Keywords: ADHD, subtypes, inhibition, oculomotor

Examining Manual and Visual Response Inhibition among ADHD Subtypes

The inattentive subtype of ADHD has been mired in controversy since the disorder was introduced in *DSM-III* in 1980. Initially the controversy concerned whether the inattentive subtype was a valid diagnostic category, although research undertaken over the past 30 years has documented the presence of a group of children who reliably meet the diagnostic criteria (Lahey & Carlson, 1991; Milich, Balentine, & Lynam, 2001). In the past 10 years the focus of the debate has shifted to whether the inattentive subtype is actually a subtype of ADHD or instead should better be categorized as a distinct and unrelated disorder (Diamond, 2005; Milich et al., 2001). However, as Milich et al. note, our understanding of the inattentive subtype is limited by conceptual and methodological problems that may preclude drawing meaningful conclusions about the relation between the two subtypes. Recent research using carefully distinguished groups of children has shown important differences between the two subtypes on measures of inhibitory functioning (Adams, Derefinko, Milich, & Fillmore, 2008;Derefinko, Adams, Milich, & Fillmore, 2008; Fillmore, Milich, & Lorch, 2009). The current study aims to continue this line of investigation by examining subtype differences on inhibitory measures as a function of response requirement (i.e., hand or eye movements). Examining manual and visual inhibitory processes seems especially appropriate for our understanding of the inattentive (ADHD/I) and combined (ADHD/C) subtypes, because the two groups are assumed to differ in the manners in which they exhibit attentional and inhibitory deficits.

Measuring Response Inhibition

When defined broadly, inhibition is the process of suppressing an inappropriate response, but the term may refer to a number of related processes, including inhibiting prepotent responses, stopping ongoing responses, and controlling interference (Barkley, 1997). According to

Barkley's (1997) influential model, deficits in response inhibition have downstream effects on other executive functions, resulting in the characteristic behavioral and academic impairments observed in ADHD. Abundant empirical evidence supports a role for inhibitory deficits in ADHD in both children and adults (Carr, Nigg, & Henderson, 2006; Nigg, 2001, 2006).

A number of assessment tools have been developed over the years to measure response inhibition (Nichols & Waschbusch, 2004; also see Nigg, 2001, Table 1). Among the most popular of these measures are variants of Logan and Cowan's (1984) stop task (Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998). The basic premise of this task is that two separate but interactive processes—a response execution or "go" process and a response inhibition or "stop" process—are engaged in an interactive "race" every time one wishes to inhibit a response (Boucher, Palmeri, Logan & Schall, 2007; Logan, 1994; Logan & Cowan, 1984; Osman, Kornblum, & Meyer, 1986). If the stop process runs to completion before the go process finishes, then the response is successfully inhibited; otherwise, a response occurs. Inherent in this model is the notion that these processes occur at different rates and thus require different amounts of time to complete. More specifically, the stop or inhibitory process must be faster than the go process, otherwise responses could not be successfully inhibited.

In the typical stop task, participants are involved in a primary task, such as quickly and accurately making differential responses to stimuli as they appear on a screen. Here, reaction times are thought to reflect the speed of the underlying go process, with mean go reaction times (RTGo) typically reported for each individual or group (Logan, 1994). Occasionally, a tone or image is presented after the initial stimulus, signaling that participants should withhold responding on those specific trials. This stop signal presumably initiates the inhibitory process

(Logan & Cowan, 1984). Stop signal reaction time (SSRT) is defined as the difference between the time the stop signal is presented and the end of the inhibitory process, and can be estimated mathematically based on observed proportion of inhibition at various stop signal delays (Logan & Cowan, 1984; Logan, 1994).

Two recent meta-analytic studies incorporating 35 independent samples have reviewed performance on this task specifically for children with ADHD (Lijffijt et al., 2005; Oosterlaan et al., 1998). Across these studies, a consistent pattern is that SSRTs are faster than RTGos for both ADHD and comparison groups (i.e., stopping is faster than going). Beyond this, a relatively stable group effect is observed whereby children with ADHD have slower SSRTs relative to comparison children, consistent with the notion that ADHD is at least partly attributable to deficits in response inhibition.

Manual vs. Oculomotor Countermanding

Despite widespread use of the stop task, it is important to note that a great deal of variability exists in the procedures used (Lijffijt et al., 2005; Oosteralaan et al., 1998). Though the traditional stop task is a valuable tool and reflects an important model for understanding inhibition, it puts great emphasis on ballistic hand movements as an indicator of inhibition. An alternative version of the stop task, called the oculomotor or visual stop task, requires participants to respond by moving their eyes rather than their hands (Armstrong & Munoz, 2003; Hanisch, Radach, Holtkamp, Herpertz-Dahlmann, & Konrad, 2006; Logan & Irwin, 2000; Schall, Hanes, & Taylor, 2006). Here, quick eye movements called saccades constitute responses. When a stop signal is presented, participants are instructed to withhold eye movement and instead fixate on a designated point or object on the screen. The oculomotor countermanding task allows researchers to explore whether the problems with response inhibition observed in

ADHD via the typical stop task apply across response modalities or if these deficits are unique to hand-motor responding. According to Logan and Irwin (2000), investigating response inhibition for eye movements is important, because (a) eye movements are controlled by separate anatomical pathways from hand movements, suggesting separate physiological mechanisms for response inhibition, and (b) visual movements often precede and improve accuracy of hand movements, implying that inhibition of eye movements may mediate inhibition of hand movements. Additionally, by measuring one's ability to appropriately inhibit one's eye movements, the visual stop task more directly represents an effort to tap into the intersection between attentional processes and inhibitory processes, which is of particular relevance to the study of ADHD.

The oculomotor countermanding paradigm has received far less scrutiny in the research literature than those tasks that require some form of hand-oriented response, particularly with respect to ADHD. Armstrong and Munoz (2003) found that adults with ADHD were less able to inhibit saccadic responses than participants in the control group. Furthermore, children with ADHD have been shown to commit more inhibitory failures and have longer SSRTs than controls on an oculomotor countermanding task, in contrast to comparable performance between groups on tasks measuring reflexive eye movements without inhibitory demands (Hanisch et al., 2006). These results corroborate earlier findings from the traditional hand-motor stop task studies (Lijffijt et al., 2005; Oosterlaan et al., 1998) whereby deficits in response inhibition uniquely characterize ADHD groups relative to control groups.

Only one direct comparison between hand and eye movement responses on the stop-signal task has been reported. In that study, the investigators were interested in clarifying whether inhibition under each response requirement was achieved via common or separate

physiological mechanisms (Logan & Irwin, 2000). As noted previously, the neural signals that initiate eye and hand movements follow a common path up to a certain point, from which these signals diverge and are completed by separate pathways. The authors tested inhibitory performance in healthy adults and found that like the manual stop task, eye movements also show that stopping is faster than going (i.e., SSRT < RTGo). However, overall, the RTGo and SSRT of eye movements is faster than hand responses (Logan & Irwin, 2000). With respect to SSRT, participants had significantly faster SSRTs for eye movements than for hand movements. The investigators interpreted overall findings as consistent with the notion that eye and hand movements are likely regulated by separate inhibitory processes operating under similar principles specified by the race model (Logan, 1994; Logan & Cowan, 1984).

The goal of the present study was to explore performance on visual and manual versions of the stop task among children with ADHD and comparison peers. In keeping with previous findings (Armstrong & Munoz, 2003; Hanisch et al., 2006; Logan & Irwin, 2001), faster reaction times are anticipated for both go (RTGo) and stop processes (SSRT) in the oculomotor countermanding task relative to a button-press manual version of the stop task. Furthermore, we anticipated shorter SSRTs than RTGo values for both versions of the stop task.

Subtype differences

With regard to ADHD, it was predicted that children with ADHD would display longer SSRTs relative to the comparison group (Lijffijt et al., 2005; Oosterlaan et al., 1998). While problems in behavioral inhibition are believed to play an important role in the development of ADHD, it is unclear how well these findings generalize across ADHD subtypes. Indeed, neither of the meta-analytic reviews on stop task performance addressed differences among ADHD subtypes (Lijffijtet al., 2005; Oosterlaan et al., 1998). Contemporary ADHD research is largely

focused on ADHD/C (Nigg, 2006), but researchers are increasingly incorporating subtype level analyses into their study designs and discussing explicitly the relations between ADHD/I and ADHD/C. Unfortunately, however, this research continues to be plagued by methodological flaws (e.g., low power, atheoretical designs, inconsistent sampling procedures) that impede our understanding of subtype differences (Adams et al., 2008; Milich et al., 2001). Perhaps the most important concern is that ADHD/I groups are often contaminated by the inclusion of subthreshold ADHD/C participants, thus rendering subsequent results and interpretations ambiguous with respect to subtype differences (Milich et al., 2001). Although such a classification strategy is consistent with *DSM-IV* diagnostic criteria (APA, 1994), this system does not necessarily reflect the most informative framework for understanding these disorders.

One solution to this methodological problem would be to develop and integrate a number of studies that incorporate diagnostic subgroups. Preliminary studies suggest that interesting patterns of similarities and differences emerge when subtype groups are clearly delineated such that participants with "pure" ADHD/I (i.e., few, if any, hyperactive/impulsive symptoms) are compared to those with ADHD/C on tasks measuring various aspects of inhibitory functioning (Adams et al., 2008, Derefinko et al., 2008, Fillmore, et al., 2008). For instance, Derefinko and colleagues (2008) found that ADHD subtype groups exhibit unique patterns of performance on tasks measuring sensitivity to environmental factors either preceding or following signals to respond or inhibit behavior. Specifically, children with ADHD/I consistently demonstrated longer response reaction times and more errors of omission, suggesting a slow, perhaps cautious response style (Derefinko et al., 2008). Fillmore and colleagues (2008) studied reflexive oculomotor inhibition among ADHD subtypes and found that reflexive inhibition was absent in the ADHD/C group, whereas this form of inhibition was only partially reduced in ADHD/I

relative to comparison children. Together, these findings suggest that interesting differences

emerge among ADHD subtypes when carefully defined groups are compared.

However, there are several areas where the ADHD subtype groups share similar

performance profiles that distinguish them from comparison groups but not from each other. For

instance, both ADHD groups tend to demonstrate more variable responding relative to

comparison groups (Derefinko et al., 2008, Fillmore et al., 2008). Although other studies make

claims regarding the similarity of the ADHD subtypes on various measures of performance, the

methodological limitations described above limit our ability to make such general claims.

Thus, as a second aim, the current study sought to examine how ADHD subtypes differ

with respect to performance on manual and visual versions the stop task. It was hypothesized that

children with ADHD/I would demonstrate slower overall reaction times relative to children with

ADHD/C and comparison children. Although both ADHD groups were expected to demonstrate

impairment relative to the comparison group on both versions of the stop task, the current study

sought to determine whether the visual stop task is more sensitive to the deficits associated with

ADHD/I compared to ADHD/C given that the visual task may more directly tap attentional

processes than the manual task.

<div align="center">Method</div>

Participants

A sample of 58 children with ADHD and 18 comparison children participated in this

study. The children in each diagnostic group were between the ages of 9 and 12 years (*M* age =

10.85 years, *SD* = 1.11). Approximately 85% of the children were Caucasian, 11% were African

American, and 4% identified themselves as other. The children with ADHD were recruited from

the Hyperactive Children's Clinic in the School of Medicine at the University of Kentucky. The

children were carefully selected to fulfill the *DSM-IV* criteria for either the ADHD inattentive

subtype or ADHD combined subtype and to ensure that they were relatively free of confounding factors. Diagnoses were based on a convergence of evidence from multiple informants and multiple measures.

Children were first required to have received the appropriate *DSM-IV* ADHD diagnosis (i.e., inattentive or combined) based on a comprehensive psychiatric clinic evaluation at the Hyperactive Children's Clinic. This evaluation utilizes multiple assessment procedures designed to identify psychiatric and neurological factors that may influence or better account for ADHD symptoms, such as mood disorders, developmental disorders, epilepsy or neurological disorders, or intellectual disability. In addition, the medical charts of all the children were reviewed in detail to gather specific information about ADHD diagnoses and medical history, including reason for clinic referral, age at onset of symptoms, classroom behavior via teacher ratings, evidence of impairment, parent ratings of behavior, IQ, medical history, and comorbid diagnoses. Children were excluded from the study if their medical charts provided evidence of IQ scores lower than 80, presence of sensory impairments, diagnoses of epilepsy or other neurological disorders, or prescribed medication that could not be temporarily discontinued during study participation. Further, children who were diagnosed by the Hyperactive Children's Clinic with ADHD primarily hyperactive/impulsive subtype were excluded from the study.

If the above criteria were met, then a parent of the child with ADHD was contacted and invited to participate in the study. During the testing session, a semi-structured interview, similar to the parent report version of the Children's Interview for Psychiatric Syndromes (P-ChIPS; Weller, Weller, Rooney, & Fristad, 1999), but only consisting of verbatim *DSM*-IV criteria for ADHD and ODD, was conducted with the parent to confirm the child's diagnostic status. This interview also provided a common measure of ADHD symptoms for all children in the study,

because the assessment measures used to make the initial clinic diagnosis varied. The interviews were conducted by trained graduate students in clinical psychology. In the interview, the parent was asked whether each diagnostic criterion is true of his/her child, and, if so, the parent was asked to give specific behavioral examples. If a behavior was characteristic of the child, the parent was additionally asked whether that behavior seems inappropriate for the child's age and whether it is impairing the child's functioning academically and/or socially. A diagnostic criterion was only considered to be endorsed if the parent indicated the behavior is both age inappropriate and impairing. This interview procedure has been used successfully by our research group in previous studies, with interrater reliabilities for the number of ADHD symptoms endorsed by the parent to be above 95%. The data for children whose parental interviews support an ADHD diagnosis were retained for analysis in this study.

In addition to the information from the structured psychiatric interview, parents were asked to complete the Child Behavior Checklist (CBCL; Achenbach, 1991) and the Conners Parent Rating Scales—Revised: Short Forms (CPRS-R:S; Conners, 1997). The CBCL is a widely used parent-report questionnaire designed to assess a wide range of behaviors and competencies in children (Achenbach, 1991). A recent study utilizing receiver-operating characteristic analysis demonstrated that the CBCL provides good diagnostic accuracy in predicting DSM-IV ADHD and ODD/CD in children ages 6 to 18 years using the cut scores specified below (Hudziak, Copeland, Sanger, & Wadsworth, 2004). The CPRS-R:S includes items from the long form of the CPRS—R on each of three subscales: oppositional, cognitive problems/inattention, and hyperactivity. The measure also includes a fourth subscale, the ADHD index, which includes ADHD symptoms derived from DSM-IV diagnostic criteria. This measure

is widely used in clinical and research settings as an indicator of the various behavioral

symptoms of ADHD as observed by a parent or caregiver (Conners, 1997).

Diagnostic Subgroups

Children with ADHD were assigned to one of the two subgroups under investigation

(ADHD/C; ADHD/I) based on the history obtained from the psychiatric chart review as well as

the more systematic data obtained from the structured interview and the CBCL and CPRS-R:S.

Consistent with the exclusionary criteria utilized at the first stage of recruitment, no children

with ADHD hyperactive/impulsive subtype were identified within this group. To be placed in the

ADHD/C group ($n = 42$), children must have met criteria for this diagnosis on the structured

interview, have T scores above 60 on the Conners Hyperactivity scale and the ADHD Index.

Consistent with the literature suggesting a common comorbidity between ADHD/C and

oppositional behavior (Weiss, Worling, & Wasdell, 2003; Nigg, 2000), children demonstrating

clinically significant conduct problems were not excluded from the ADHD/C group. In forming

the ADHD/I group ($n = 16$), recommendations made by Milich et al. (2001) were followed to

ensure that this group did not include subthreshold ADHD/combined children. Specifically,

children in the ADHD/I group were required to meet criteria for attention problems on the

structured interview and had 3 or fewer symptoms on the hyperactive/impulsive dimension. In

addition, these children had T scores above 60 on the Conners Cognitive Problems/Inattention

scale and T scores less than 60 on the Hyperactivity scale. Finally, the children in the ADHD/I

group had T scores below 60 on the CBCL Aggression and Delinquency scales.

The comparison group of children without ADHD ($n = 18$) was recruited through

newspaper advertisements, posted advertisements in the community, and by word-of-mouth.

They were screened during a recruitment phone call in which parents were asked if their children

had ever been referred for any behavioral or learning problems. The comparison children were not required to be symptom free, but had to have two or fewer symptoms in a diagnostic category. These children were significantly less symptomatic than the children with ADHD in terms of the *DSM-IV* criteria for inattention symptoms and hyperactive symptoms, and moreover did not meet diagnostic criteria for any ADHD subtype. In addition, the children in the comparison group were required to have T scores below 60 on all of the relevant rating scales. As indicated in Table 2.1, the diagnostic interview and rating scale data successfully differentiated between the comparison, ADHD/I, and ADHD/C groups.

Among the children with ADHD, roughly two-thirds were being treated with psychostimulant medication. The remaining children were not taking any prescribed medication at the time of the study. No child received any psychostimulant medication on the day of the study until after the session was completed. This provided a sufficient time period (approximately 24 hours) for clearance of any medication administered on the day before the session. Participants who were receiving other medications that could not be easily withdrawn for testing (e.g., clonidine) were excluded at the time of enrollment. All children received two small toys and $30.00 for their participation in the study.

Groups were not significantly different on the basis of age, gender, racial composition, grade level, maternal education, paternal education, or KBIT vocabulary scores (see Table 2). A significant difference between groups was observed, however, for KBIT matrices scores, $F(2, 73) = 3.86$, $p = .025$, with comparison children receiving higher scores than both ADHD groups. When KBIT matrices scores were included as a covariate in the analyses reported below, the same pattern of group similarities and differences emerged for all stop task dependent variables.

This suggests that the observed differences between groups on stop task measures were not accounted for by group differences in KBIT matrices performance.

Procedure

All procedures were approved by the Institutional Review Board at the sponsoring institution. The study took place at the Behavioral Pharmacology and Neurocognition Research Laboratory in the Department of Psychology at the University of Kentucky. All children were tested individually on non-school days between the hours of 9 am and 5 pm. Upon arrival at the lab the child and parent were greeted by two experimenters who described the general details of the study and the basic testing procedures. Written consent was then obtained from the parent, as well as verbal assent from the child. After obtaining consent, one of the experimenters accompanied the parent to an interview room to complete the semi-structured interview and questionnaires. The other experimenter accompanied the child to a nearby testing room to complete the testing. The administration of these tasks was part of a larger testing battery involving neuropsychological tests and other measures of cognitive functioning took roughly 3 hours to complete. Prior to each test, the experimenter provided the task instructions and children performed a brief, 2-3 min familiarization test to ensure that the child understood the task requirements. Children were given a 15-minute break between each testing component. At the conclusion of the session, the child and parent were debriefed and paid for their participation. Experimenters rotated parent interviewing and child testing responsibilities and were blind to participants' clinical diagnostic status to reduce the risk of experimenter effects on responding and performance.

Measures

  *Manual Stop Task (MS).*The manual stop (MS) task was used as a measure of behavioral

inhibition. The MS task requires participants to press a button when a stimulus (go signal)

appears on the screen, but to withhold responding when a stop signal tone is presented. The go

signals—white circles measuring 8 mm in diameter—were presented individually. Each trial

began with a 1000 msec presentation of a plus sign (+) in the middle of the computer display.

This served both as a location for participants to fixate their attention and as an indication that a

trial was about to begin. As soon as the plus sign disappeared, a circle appeared in one of four

positions: far right (12 cm from center), middle right (6.5 cm from center), far left (12 cm from

center), middle left (6.5 cm from center). Participants were required to press the forward slash

key (/) on a standard computer keyboard as soon as they detected a circle on the right or the

period key (.) if the circle is on the left, using their middle and index fingers, respectively. The

circle was present on the screen for 1 second. A blank screen appeared for 1500 ms before the

start of the next trial. The complete task involved 128 trials, with each of the four stimulus

positions presented an equal number of times (32 times). A stop signal tone occurred on 32 trials

(i.e., 25% of the time), equally distributed among circle positions. The stop signal was a 500 ms

900 Hz tone generated by the computer at a comfortable listening level. Participants were

instructed to withhold (i.e., inhibit) their response when a stop signal is presented. Stop signals

were presented eight times at each of four stimulus onset asynchronies (SOAs; i.e., delays: 50,

150, 250, and 350 ms) with respect to the onset of the circle presentation. The order of circle

locations, stop signal presentation, and delays was random. A test required approximately 8

minutes to complete.

  The primary dependent variable for the stop task is the SSRT, which represents an

estimate of the time it takes an individual to withhold a response. SSRT is calculated here according to Logan (1994), consistent with Oosterlaan et al. (1998) and is averaged across diagnostic subgroup. Another indicator of inhibitory functioning as measured by the stop task is the proportion of inhibitory failures (i.e., responding following a stop signal) committed by the participant over the course of the task. In the current study, the intrasubject variability on go trials (GoRT$_{SD}$)was evaluated as a measure of inattention (Klein, Wendling, Huettner, Ruder, & Peper, 2006). Omission errors were also considered as an indicator of inattention, as greater variability in responding can result in missed responses on go-trials. Reaction time for go trials was measured as an indicator of overall response speed. This variable was also used to calculate the potential trade-off between speed and accuracy (i.e., successful inhibitions) for each group. Finally, choice errors (i.e., hitting the incorrect button on a go trial) were also measured.

*Visual Stop Task (VS).*The visual stop (VS) task was similar to the MS task, but required participants to move their eyes in response to go signals rather than pressing a button. Participants were instructed not to look at the stimulus when a stop signal was presented. With the exception of response requirement, all other task characteristics were the same as those described for the MS task.

Because the eye tracker was stationary, it was important for participants' eyes to be at a constant location relative to the screen. As such, participants' chins were placed in a chin rest to stabilize head movement and to maintain a constant 27 cm distance between the participant and the computer display throughout the task.

Response inhibition was measured on a test by the number of times that an individual successfully inhibited an eye movement on all 32 stop-signal trials (i.e., eye movement that was less than half the distance to the target was a successful inhibition). Response activation was

measured by the mean RT to the go trials (i.e., the average time from the onset of a circle

presentation until the first visual fixation point, indicating the completion of the primary

saccade). Eye movements were recorded using a Model 504 Eye Tracking System (Applied

Science–Laboratory, Boston MA). Eye locations were sampled at 60 Hz and given an X/Y

coordinate. These coordinates were used to define fixations and saccades. The distance of a

saccade and its duration were then calculated using fixation onset and offset times. Onsets of

fixations were defined as periods of at least 100 msec in which the line of gaze had a standard

deviation of less than 0.5 degrees of visual angle. Offsets of fixations were determined by

periods of at least 50 msec in which the gaze position was at least 1 degree of visual angle away

from the initial fixation position. The final fixation position was the average of all data sampled

between the beginning and end of the fixation.

Statistical analysis

Initial descriptive analyses were performed to explore equivalence across groups with

respect to demographic variables. Specifically, between-groups comparisons (i.e., one-way

ANOVAs) for sex, age, race, parental education, and estimated IQ were performed to ensure that

any observed group differences on response inhibition variables were not due to non-equivalence

on these demographic characteristics.

To evaluate inhibitory performance, SSRTs were calculated for each subject and were

subjected to planned contrasts to determine whether comparison children differed significantly

from children diagnosed with ADHD and whether children with ADHD/I differed from children

with ADHD/C. Similar analyses were performed to compare the groups with respect to

proportion of inhibitory failures, RTGo, variability in responding, and omission errors.

Additionally, mixed repeated measures ANOVAs were performed to examine whether stop task

performance differed as a function of response requirement (manual, visual) or group

(comparison, ADHD/I, ADHD/C). These analyses also included a factor for measure (SSRT,

RTGo) to compare speed of inhibiting to the speed of executing a response.

<div align="center">Results</div>

Response inhibition: SSRT and inhibitory failures

Results for the manual and visual versions of the stop task can be found in Table 3.

Comparisons of SSRT between the visual and manual tasks indicated that children were slower

to inhibit (i.e., longer SSRTs) on the visual task than on the manual task, $t(67)$ 4.36, $p < .001$, $d =$

.59 (see Table 4). For the manual task, independent samples t tests revealed significant

differences between the comparison group and ADHD groups for SSRT, such that children with

ADHD were significantly slower to inhibit responses than were comparison children, $t(74) =$

2.40, $p < .05$, $d = .58$. No subtype difference was observed for SSRT, however, $t(74) = .54$, *ns*. A

similar pattern was observed on the visual task for SSRT whereby both ADHD groups were

significantly slower in inhibiting responses than comparison children, $t(74) = 3.01$, $p < .01$, $d =$

.70. Again, the subtype groups were not significantly different from each other, $t(73) = .23$, *ns*.

Although SSRT is derived partially from the proportion of inhibitory failures a

participant commits, it is important to examine this variable as a component of the SSRT

estimate. Children committed more inhibitory failures on the visual task than the manual task,

$t(67) = 4.35$, $p < .001$, $d = .55$. Children with ADHD/C were predicted to commit more inhibitory

failures than comparison children and children with ADHD/I. However, in the present study

contrasts revealed there were no subtype group differences for this variable on either the manual

task, $t(57) = .56$, *ns*, or the visual task, $t(49) = .23$, *ns*.

Response Speed

With respect to RTGo, children in all three groups had faster responses on the visual task than the manual task, $t(67) = 12.61$, $p < .001$, $d = 2.11$. On the manual task, children with ADHD/I responded more slowly to go trials than did children in the comparison, $t(73) = 2.13$, $p < .05$, $d = 1.04$, or ADHD/C groups, $t(73) = 2.17$, $p < .05$, $d = 0.83$. Children in the comparison and ADHD/C groups did not significantly differ from each other with respect to go-trial reaction time, $t(73) = .33$, *ns.* Although the ADHD/I group was relative slower than the other groups on the manual task, no group differences were observed for RTGo on the visual task.

The difference between the RTGo and SSRT was examined for each group across the two tasks. Consistent with previous work, SSRT was faster than RTGo on the manual version of the stop task for all groups (see Figure 1). The speed advantage of stopping was also observed in the visual task, but only in the comparison group, $F(1, 19) = 7.13$, $p < .05$, $d = 1.22$. Suprisingly, children in the ADHD groups did not demonstrate this disparity. Instead, RTGo and SSRT values were similar on the visual stop task in both the ADHD/I group, $F(1, 13) = 1.13$, *ns*, and ADHD/C group, $F(1, 36) = 1.32$, *ns*.

Attention

In the current study, the intrasubject cross-trial variability on go trials (GoRT$_{SD}$) was evaluated as a measure of inattention. Both ADHD groups were significantly more variable than the comparison group on both the manual, $t(74) = 2.73$, $p < .01$, $d = .63$, and visual versions of the stop task, $t(43) = 3.28$, $p < .01$, $d = 1.00$. However, children with ADHD/I did not differ from their peers with ADHD/C on either the manual, $t(74) = .63$, *ns*, or visual $t(74) = .12$, *ns*, tasks. Within-subjects differences were observed for GoRT$_{SD}$ between versions of the task, whereby children were more variable on the visual task than the manual task, $F(1, 65) = 42.37$, $p < .001$, d

= 1.57. With respect to omission errors, no statistically significant differences were observed

across groups for either version of the stop task, $F(2, 73) = 1.44$, *ns*. However, more omission

errors were committed by all groups on the visual task than on the manual task, $t(67) = 3.36$, $p <$

.01, *d*= .52.

Discussion

The purpose of the current study was to compare performance patterns on two versions of

the stop task—manual and visual—among children diagnosed with ADHD and their peers. A

second goal was to explore whether there are differences in performance between clearly defined

ADHD subtype groups relative to their peers. Results indicated that children in both ADHD

groups demonstrated longer SSRTs relative to the comparison group, which supports previous

work implicating impaired response inhibition in ADHD. Although SSRT values were faster

than those for RTGo in the comparison group on both versions of the stop task, consistent with

the broad body of previous research on stop task performance (Lijffijt et al., 2005; Oosterlaan et

al., 1998), this pattern was only observed on the manual task for the ADHD groups. On the

visual task, children with ADHD took as long to stop as they did to go (i.e., no difference

between RTGo and SSRT). Thus, the slowed inhibition associated with ADHD was most

pronounced in the visual domain. Finally, except for RTGo for the manual task, the ADHD

subtype groups did not differ from children with ADHD/C, suggesting that the stop task may not

be an effective tool for differentiating the subtypes.

Task comparisons

To our knowledge, this is the first study to evaluate performance on both manual and

visual versions of the stop task in a sample of children with ADHD compared to children without

the disorder. Although the traditional, button-press stop task has been studied extensively, less is

known about the relative utility of using the visual task to understand the cognitive deficits underlying ADHD. Given that eye movements are involved in basic attention processes, studying the ability to withhold saccades may afford a clearer understanding of the interface between attention and inhibition, two processes implicated in the ADHD.In comparing manual and visual versions of the stop task, similar patterns of impairment were observed across both tasks in the ADHD groups relative to the comparison group. Children with ADHD required more time to successfully inhibit responses than did children in the comparison group. There were no differences between the ADHD subtype groups with respect to measures of inhibition, however. Thus, it may be that the capacity to inhibit responding, particularly eye movements, is a measure of the inattentive symptoms that characterize both subtypes rather than the behavioral symptoms that are more intuitively linked to disinhibition.

One of the most notable findings from the current study concerns the differences in the time required to inhibit versus execute responses in each task. Previous studies of stop task performance in ADHD suggest that the typically observed pattern of faster SSRT relative to RTGo is stable and robust (e.g., Oosterlaan et al., 1998; Lijffijt et al., 2005). All children showed this pattern on the manual task. However, on the visual task this pattern was reversed in the two ADHD subtypes. Children with ADHD showed no difference between RTGo and SSRT on the visual stop task. Given that response activation processes are initiated prior to inhibitory processes, this means that for children with ADHD, executing saccades took place at a more rapid pace than the ability to stop them. This unexpected similarity between rates of going and stopping could be due to faster response activation (shorter RTgo) or slower response inhibition (longer SSRT). Figure 1 shows that RTGo values were similar across all three groups on the visual task. However, SSRT values were slower in both ADHD groups, indicating that the

unique relation between RTGo and SSRT on the visual task in ADHD is a function of some component involved in response inhibition, especially as it relates to the attentional system.

In understanding this finding, it is important to consider the value of being able to inhibit a behavior more quickly than activating a behavior. Put simply, quick inhibitory processes improve the flexibility of one's behavioral repertoire and increase the likelihood that one will be able to act in accordance with changing demands in the environment. When stopping is slower than going, or even if stopping takes place at the same rate on average as going, it becomes difficult for individuals to regulate their behavior in the face of dynamic environmental conditions. That the unique relation between RTGo and SSRT among children with ADHD was specific to the visual task also carries implications for our understanding of the disorder. For instance, children with ADHD could experience impaired control over selective attention processes and exhibit increased distraction because they have difficulty ignoring irrelevant stimuli in the environment (i.e., problems inhibiting reflexive looks) even when they are effortful in attempts to do so.

Taken together, these findings suggest that the visual stop task may be a more sensitive measure of inhibitory impairment in ADHD. This sensitivity may be due to the visual task's reliance on inhibiting eye movements, which reflects an interface between attentional processes and inhibition. In this way, ocular countermanding may be a closer analog to the kinds of difficulties children with ADHD experience that underlie symptoms of inattention.

Subtype comparisons

A second purpose of the current study was to examine subtype differences on manual and visual versions of the stop task with well-defined subtype samples. Previous work from this research group as suggested important differences between the two subtypes, including slow

response speed and increased omissions in ADHD/I group relative to ADHD/C (Derefinko et al., 2008; Fillmore et al., 2009).In the present study, performance of the two ADHD subtypes was quite comparable across both tasks, especially for measures of inhibition. The only exception was for RTGo, whereby children with ADHD/I were slower than children with ADHD/C to execute a response on the manual task. This finding is consistent with a slower response style observed on other tasks for the ADHD/I group (Derefinko et al., 2008; Fillmore et al., 2009). In some contexts, slower responding confers greater accuracy in responding or withholding a response. However, the slower responding observed in the ADHD/I group in the current study did not afford protection from inhibitory failures. Indeed, the ADHD/I group had the slowest RTGo values on the manual task but still had many more inhibitory failures than the comparison group, which had relatively faster RTGo values.

Although some measures yield distinct patterns of performance between the ADHD subtypes, others yield quite similar results (Adams et al., 2008). That the ADHD subtype groups in the current study did not differ with respect to inhibitory performance on the stop task is consistent with other studies examining response inhibition among ADHD subtypes (e.g., Geurts, Verte, Oosterlaan, Roeyers, & Sergeant, 2006). Beyond simply replicating these previous findings, however, the use of clearly defined subtype groups in the current study extends our understanding of the mechanisms underlying "pure" ADHD/I with very few to no hyperactive/impulsive symptoms.

The similarity between the ADHD/C and ADHD/I groups on the stop task warrants further consideration, given conflicting evidence that the subtype groups are quite distinct in other areas of cognitive and behavioral functioning (i.e., Adams et al., 2009; Diamond, 2005; Milich et al., 2001). One possible explanation as to why the stop task did not differentiate the

subtype groups is that ADHD/I is a disorder of disinhibition, sharing this "core" deficit with ADHD/C. This would support the notion that ADHD/I is best conceptualized as a phenotypic variant of ADHD but not necessarily as a distinct disorder. This view is complicated, however, by findings that show inhibitory deficits for the ADHD/C group on some tasks that are not present for the ADHD/I group. Further, on some tasks where children with ADHD/I show significant differences from a comparison group, the direction of the effect is in the opposite direction than might be expected based on performance in the ADHD/C group (Derefinko et al., 2008). That is, children with ADHD/I at times appear *overly* inhibited rather than disinhibited. Thus, it is difficult to reconcile the current findings with those of previous work examining inhibitory performance in the same sample using different tasks.

An alternate interpretation is that the observed similarity between the subtype groups reflects unique deficits that result in longer SSRT values relative to the comparison group. The stop task is clearly capturing a deficit in both subtype groups, but it is possible that the similar outcomes observed derive from separate developmental pathologies. In this case, ADHD/I may not be an inhibitory disorder, but rather the result of some other kind of information processing deficit. To illustrate, a child who is generally slow to process environmental stimuli or other information necessary to guide behavior would be expected to appear slow in activating a response as well as slow to inhibit a response. This is consistent with the pattern we observe in the ADHD/I group on the manual task. Thus, the stop task may be sensitive to other kinds of deficits beyond gross disinhibition, such as slow information processing.

Interestingly, the difference between the ADHD/I and ADHD/C groups for RTGo was not observed on the visual stop task. This finding, in tandem with the aforementioned unique relation between RTGo and SSRT in the ADHD groups, suggests that the visual stop task

measures some unique component of responding from the manual stop task. This difference should be examined further in future research.

Implications for future work

In the current study, a unique pattern relating SSRT to RTGo was observed for the ADHD groups relative to the comparison group on the visual, but not the manual, stop task. This suggests that there may be enhanced sensitivity of using eye movements in considering inhibitory functioning in ADHD. The oculomotor countermanding task may prove to be a particularly valuable tool for studying differences between children with ADHD and their peers because of its focus on attentional performance. Although the methods are more complicated for the visual task than for conventional inhibitory tasks, it seems to be a worthwhile methodology to pursue in future work.

Although the stop task was effective in differentiating ADHD groups from comparison children, there seems to be limited utility in using gross measures of behavioral inhibition to differentiate the ADHD subtype groups. Other areas of impairment may prove more fruitful explaining the behavioral differences observed between these groups. Indeed, several other clinically relevant variables beyond inhibitory functioning have been proposed as important to the neurocognitive profiles of ADHD subtypes. Among the most likely candidates for the deficits observed in ADHD/I are working memory (Diamond, 2005), attention (Huang-Pollock et al., 2005; Huang-Pollock et al., 2006), motivation (Quay, 1997), various executive functions (Nigg et al., 2002; Pennington & Ozonoff, 1996), slow information processing (Carlson & Mann, 2002; Derefinko et al., 2008, Fillmore et al., 2008) and the complicated interplay among these processes. Further, studying the ADHD subtypes across multiple levels of analysis beyond basic neurocognitive tasks (i.e., physiological measures, genetic markers and family history, complex

behaviors, long-term outcomes, etc.) will allow better understanding of the factors that account for areas of continuity and discontinuity between the subtypes, toward the goal of developing a more integrative model of ADHD/I. A substantial amount of work along these lines has already been conducted with the ADHD/C group, but relatively little has been done to evaluate the inattentive subtype and its relation to other disorders, including ADHD/C.

In summary, the current results indicate that while an oculomotor version of the stop task may be more sensitive to the inhibitory deficits observed in ADHD relative to children without ADHD, neither the visual nor the manual stop task were effective in differentiating the ADHD subtypes. This reflects an interesting area of behavioral overlap between two groups of children who have demonstrated unique patterns of continuity and discontinuity on other measures, including other tasks designed to measure disinhibition. This suggests that further study of neurocongitive functioning among ADHD subtypes is a potentially fruitful avenue for better understanding how these diagnostic constructs relate.

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Table 1

Diagnostic Information by Group

Variable	Comparison (n = 18)	ADHD/I (n = 16)	ADHD/C (n = 42)	F	t result
Age diagnosed with ADHD (years)		8.2 (0.9)	7.3 (2.3)	1.88	
DSM-IV attention	0.5 (1.1)	6.2 (2.6)	7.3 (1.9)	91.23***	a
DSM-IV hyperactivity	0.4 (0.7)	1.5 (1.5)	5.5 (2.4)	61.83***	b
DSM-IV oppositional/defiant	0.2 (0.4)	1.1 (1.3)	2.2 (2.2)	26.36***	b
Connors oppositionality	42.8 (3.9)	50.4 (8.3)	61.5 (12.0)	27.92***	b
Connors cognitive problems/inattention	45.1 (3.8)	71.5 (9.3)	72.9 (8.6)	96.58***	a
Connors hyperactivity	47.8 (5.1)	53.1 (11.6)	76.9 (10.3)	80.69***	b
Connors ADHD total	44.7 (3.3)	68.5 (8.5)	74.7 (6.6)	156.81***	c
CBCL aggression	51.1 (3.9)	54.4 (5.9)	62.4 (9.7)	16.62***	b
CBCL delinquency	51.4 (2.8)	53.2 (5.7)	58.9 (8.3)	10.02***	b

Note. $*p < .05$, $**p < .01$, $***p < .001$. ADHD/I = ADHD inattentive. ADHD/C = ADHD combined. *DSM-IV* scores based on semi-structured interview. a. Comparison significantly different from 2 ADHD groups. b. ADHD/C significantly different from comparison and ADHD/I groups. c. Comparison significantly different from ADHD/I, and ADHD/I significantly different from ADHD/C.

Table 2

Demographic Information by Group

Variable	Comparison (n = 18)	ADHD/I (n = 16)	ADHD/C (n = 42)	F	X^2	p
Age (months)	131.2 (11.3)	125.1 (13.6)	131.8 (14.0)	1.61		.206
Gender (% male)	66.7	64.7	83.7		3.51	.173
Race (% white)	85.7	76.5	88.4		1.51	.470
Grade level	5.5 (1.1)	4.7 (1.2)	5.1 (1.2)	1.99		.143
Mother's education	16.4 (1.7)	15.3 (2.0)	15.6 (2.6)	1.24		.296
Father's education	16.0 (2.0)	16.0 (3.3)	14.3 (3.4)	2.83		.065
KBIT vocabulary	107.2 (11.8)	102.9 (13.4)	102.0 (14.3)	1.08		.345
KBIT matrices	120.1 (13.3)	109.7 (12.4)	106.6 (21.8)	3.86		.025*

Note. ADHD/I = ADHD inattentive. ADHD/C = ADHD combined. KBIT = Kaufman Brief Intelligence Test. Parental education is provided in years. *For KBIT matrices, both ADHD subgroups obtained lower scores than healthy comparison children. No differences were observed among ADHD subgroups, however.

Table 3
Stop Task Performance by Group

Variable	Comparison (n = 18)	ADHD/I (n = 16)	ADHD/C (n = 43)	ADHD vs. Comp. t	ADHD/C vs. ADHD/I t
Manual					
SSRT	285.5 (67.2)	358.6 (125.8)	335.4 (87.3)	2.40*	.54
Inhibitory failures (%)	44.4 (18.4)	50.2 (26.5)	54.2 (23.8)	1.21	.59
RTGo	509.8 (58.6)	564.2 (86.2)	527.5 (80.4)	1.54	1.90[†]
RTGo$_{SD}$	126.7 (22.2)	141.1 (27.5)	145.1 (18.9)	2.73**	.63
Omission errors	3.6 (5.6)	7.3 (5.7)	8.4 (12.7)	1.51	.35
Visual					
SSRT	316.1 (73.4)	432.6 (159.6)	423.5 (152.0)	3.01**	.21
Inhibitory failures (%)	59.8 (22.2)	71.4 (28.0)	69.6 (25.2)	1.57	.24
RTGo	370.0 (65.7)	380.0 (65.7)	389.9 (58.6)	.88	.51
RTGo$_{SD}$	141.9 (37.2)	178.5 (41.8)	177.1 (40.8)	3.28**	.12
Omission errors	8.0 (9.0)	9.9 (6.8)	11.5 (14.2)	.84	.44

Note. [†]$p < .06$, *$p < .05$, **$p < .01$. ADHD/I = ADHD inattentive. ADHD/C = ADHD combined. Comp = comparison.

Figure Caption

Figure 1.Comparison of reaction time for go trials (RTGo) and stop signal reaction time (SSRT)

by group on manual and visual versions of the stop task. Asterisks denote significant differences

between RTGo and SSRT, *p*< .05.