THE CONTRIBUTION OF ATTENTIONAL CONTROL AND WORKING MEMORY TO READING COMPREHENSION AND DECODING

A Thesis

Presented to

The Faculty of the Department of Psychology

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

By

Candice N. Arrington

December, 2012
THE CONTRIBUTION OF ATTENTIONAL CONTROL AND WORKING MEMORY TO READING COMPREHENSION AND DECODING

An Abstract of a Thesis
Presented to
The Faculty of the Department of Psychology
University of Houston

In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

By
Candice N. Arrington

December, 2012
Abstract

Working memory plays an important role in the development of a coherent representation of information being read in text, which is necessary for adequate reading comprehension. Individual differences in working memory are significantly impacted by the attentional control functions of the central executive, the controlling mechanism of working memory. Attentional control is comprised of a group of functions; response inhibition, sustained attention, and cognitive inhibition. In the current study, I addressed the relation of reading comprehension, decoding skills, working memory, and attentional control in 1134 adolescent students from grades 6 - 12. The results revealed that sustained attention and cognitive inhibition, but not response inhibition, were significantly related to working memory. Hierarchical multiple regression analyses indicated a differential relation between attentional control and reading comprehension versus decoding. Sustained attention and cognitive inhibition significantly contributed to reading comprehension while response inhibition was a significant predictor of decoding ability. These results indicate that working memory operates differently in relation to decoding and comprehension due to differential associations of attentional control and working memory.

Keywords: working memory; attentional control; response inhibition; cognitive inhibition; sustained attention; reading comprehension; decoding
Acknowledgements

“To all the remarkable,
maddening, challenging,
frustrating people who inspire us
to do great things.”
~ Richard Castle

There have been so many remarkable people in my life that have driven me to do great things, most of which I never even thought possible. The actualization of this thesis (and the degree that accompanies it) is only a drop in the bucket. It is your little nudges, and sometimes big shoves, that drive me forward. Each moment and each one of you have helped to make great things happen, whether you know it or not. For this, and all the things in my life that I owe to all of you, I will be eternally grateful. Thank you for inspiring me to greatness, always.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>iv</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Current Study</td>
<td>14</td>
</tr>
<tr>
<td>Method</td>
<td>16</td>
</tr>
<tr>
<td>Participants</td>
<td>16</td>
</tr>
<tr>
<td>Procedures</td>
<td>17</td>
</tr>
<tr>
<td>Measures</td>
<td>17</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>20</td>
</tr>
<tr>
<td>Results</td>
<td>21</td>
</tr>
<tr>
<td>Discussion</td>
<td>28</td>
</tr>
<tr>
<td>References</td>
<td>39</td>
</tr>
</tbody>
</table>
List of Tables

Table 1. Descriptive Statistics for All Variables by Grade  ..................... 21
Table 2. Intercorrelations Among Variables  ........................................... 23
Table 3. Hierarchical Multiple Regression Analysis Predicting Working Memory 25
Table 4. Hierarchical Regression Analysis Predicting GMRT Lexile  ........... 27
Table 5. Hierarchical Regression Analysis Predicting TOWRE Decoding ..... 28
The Contribution of Attentional Control and Working Memory to Reading Comprehension and Decoding

Proficient reading requires the successful utilization and coordination of a number of cognitive processes. These processes operate at the level of word reading, such as phonological decoding and vocabulary knowledge (Cain, Oakhill, & Bryant, 2004; Rapp, van den Broek, McMaster, Kendeou, & Espin, 2007). Text level processes, such as inference making to maintain causal coherence, are critical for comprehension. Together, the lower level processes associated with decoding and higher level processes associated with comprehension, contribute to the development of a coherent representation of the text through their effects on working memory (WM). For both decoding and comprehension, WM is essential for holding and manipulating features of the text.

In the “simple view” of reading, proficiency is the product of decoding and linguistic comprehension (Gough & Tunmer, 1986; Hoover & Gough, 1990). Decoding can be defined as the ability to use commonalities between words and their alphabetic representation in order to successfully read new words, as well as pseudowords (Perfetti, 1985). The cognitive processes most commonly associated with decoding include phonological awareness, processing speed, and naming speed (Christopher et al., 2012; Stanovich, 1982). Adequate decoding skills are needed to identify printed words and to learn new words from continued exposure or gain word-specific knowledge of atypical words (Shankweiler et al., 1999). Word recognition skills associated with good decoding are necessary for satisfactory reading ability, but do not equate with reading proficiency, which is typically defined as the capacity to abstract meaning from print.
Linguistic comprehension represents multiple language-related processes that allow the reader to make sense of the linguistic elements of printed text (Catts, Adlof, & Weismer, 2006). In the simple view, linguistic comprehension is defined as the ability to utilize knowledge of and experience with spoken language in relation to the text being read (Hoover & Gough, 1990; Shankweiler et al., 1999). These processes are important in comprehension of not only text but also for spoken language or narrative discourse.

Linguistic comprehension and decoding function together to produce adequate reading comprehension. In Perfetti’s (1985) verbal efficiency theory, lower level processes that support decoding interact with higher level processes that support comprehension. Lower level processes must be well-learned and automatized in order to free cognitive operations that support comprehension. Decoding is specific to reading and allows for the translation of printed words into language. Linguistic comprehension typically represents more general language and cognitive processes that are required for the comprehension of spoken and written language. Research supports the dissociation of decoding and linguistic comprehension as distinct components of reading comprehension (Aaron, Joshi, & Williams, 1999; Catts et al., 2006; Gough & Tunmer, 1986; Hoover & Gough, 1990; Levy & Carr, 1990; Oakhill, Cain, & Bryant, 2003). Cain et al. (2004) found that differing cognitive skills account for unique variance in reading comprehension and decoding, identifying them as correlated, but distinct reading abilities. Deficits in either decoding ability or linguistic comprehension can result in poor reading comprehension, presumably through the operation of cognitive processes that underlie decoding and comprehension.

Working Memory
WM is a temporary storage and processing system that is necessary for a range of cognitive tasks (Baddeley, 1986; Daneman & Carpernter, 1980; Daneman & Merikle, 1996; Oakhill, 1993). It is necessary for successful reading and is involved with both single word decoding and comprehension of longer texts (Christopher et al., 2012). In decoding, WM operates to access and monitor speech-based information (Swanson, Zheng, & Jerman, 2009). For reading comprehension, WM facilitates the reader’s ability to recognize, retain, and manipulate words and their meaning in the context of the text, in order to construction a coherent, meaning-based representation of the information being read (Cain, 2006; Christopher et al., 2012). WM has been shown to be significantly related to both decoding and reading comprehension, with deficits in WM evident in poor readers whose poor reading skills stem from either decoding or comprehension difficulties (Christopher et al., 2012; Sesma, Mahone, Levine, Eason, & Cutting, 2008; Swanson, 1993). Students with poor reading comprehension skills perform more poorly on WM tasks, relative to those with good comprehension skills (Cain, Oakhill, & Lemmon, 2004; Daneman & Merikle, 1996; De Beni & Palladino, 2000; Swanson, Howard, & Saez, 2006; Turner & Engle, 1989; Yuill, Oakhill, & Parkin, 1989). Less skilled comprehenders’ poor performance may result from an inability to efficiently access recently processed information within WM (Gernsbacher & Faust, 1991). Similarly, students defined by poor decoding ability also differ from adequate readers on WM tasks (Swanson, 1999; Swanson et al., 2009). A meta-analysis conducted by Swanson et al. (2009) found that adequate readers typically outperform students with poor decoding skills on measures of WM ability. While both poor decoders and those students with poor reading comprehension not associated with poor word reading skills
(i.e., poor comprehenders) both show evidence of deficits in WM, research indicates that WM may operate differently in decoding ability and reading comprehension (Catts et al., 2006; Christopher et al., 2012; Cutting, Materek, Cole, Levine, & Mahone, 2009; Locascio, Mahone, Eason, & Cutting, 2010; Swanson et al., 2006). In particular, skills related to the central executive component of WM may be differentially involved in WM contributions to decoding and comprehension.

The central-executive is one of three functional components in Baddeley’s multiple-component model of WM that act together for the production of the moment-by-moment monitoring, processing, and maintenance necessary for information processing associated with reading comprehension (Baddeley & Hitch, 1974; Baddeley & Logie, 1999). In addition to a central executive controlling mechanism, two subsidiary systems are responsible for the processing and maintenance of verbally encoded information (phonological loop) or visual/spatial information (visuospatial sketchpad). The phonological loop and visuospatial sketchpad act as slave systems to the central executive. A key function of the central executive is the allocation of attentional resources (Barrett, Tugade, & Engle, 2004). The central executive’s control of attention aids in the resistance of irrelevant distracters, whether they be from the external environment or from internal thoughts and/or feelings. Individual differences in WM are significantly impacted by individual differences in the ability to control attention. This attentional control (AC) process is crucial for the control of cognitive processes supporting language and reading comprehension (Gathercole & Baddeley, 1993).

For efficient reading to occur, information that is read, in addition to relevant prior knowledge, must be activated, maintained, and updated in WM (De Beni, Palladino,
Pazzaglia, & Cornoldi, 1998; Gernsbacher & Faust, 1991; van den Broek, Rapp, & Kendeou, 2005). This allows for the information to be managed, in order to produce a relevant and coherent understanding of the text. This process can be passive and autonomous, and is dependent on the efficient allocation of WM resources (Gathercole & Baddeley, 1993; van den Broek et al., 2005). Successful allocation of resources from WM allows for the maintenance and continual updating of information necessary to preserve a meaningful construction of text (Gathercole & Baddeley, 1993; Pimperton & Nation, 2010). A coherent understanding is obtained through the automatic monitoring of memory-based reading processes (Conner, 2009; van den Broek et al., 2005). These mechanisms, activated during reading, are monitored by the central executive and when necessary, may be interrupted in response to a problem and replaced with alternate processes (Conner, 2009; Gathercole & Baddeley, 1993). For example, deliberate actions such as rereading poorly decoded text or pausing to allow for additional processing of information may occur when a problem is detected (Conner, 2009).

**Attentional Control**

The allocation of resources needed to regulate WM relies heavily on the AC functions of the central executive (Gathercole & Baddeley, 1993). AC involves mechanisms that coordinate both the automatic and effortful processes of WM. AC refers to the ability to inhibit irrelevant, automatic, or prepotent responses and initiate those processes which are more relevant, in addition to concurrently maintaining attention on task relevant information (Conners, 2009). This is necessary for the suppression of inappropriate information and/or responses as well as the focus on or selection of relevant information. The smooth coordination of these processes, resulting
from the efficient use of AC mechanisms, should positively impact reading proficiency and promote a coherent understanding of the text. Inconsistent AC would impede the focus needed for maintaining and updating WM, while at the same time limiting the ability to suppress or ignore irrelevant or interfering information (Flory et al., 2006).

Suppression mechanisms associated with AC may be instrumental for both successful reading comprehension and adequate decoding skills (Gernsbacher & Faust, 1991; van der Sluis, de Jong, & van der Leij, 2007). Research indicates that poor comprehenders have less efficient suppression or inhibition mechanisms that may lead to an overburdening of the WM system, and thus interferes with successful comprehension (De Beni et al., 1998; Flory et al., 2006; Gernsbacher, 1996). Additionally, poor decoders also exhibit evidence of deficits in AC mechanisms that negatively impact reading (de Jong, Van De Voorde, Roeyers, Raymachers, Oosterlaan, & Sergeant, 2009; Purvis & Tannock, 2000; Schachar & Logan, 1990; Van De Vorde, Roeyers, Verte, & Wiersema, 2010). Poor readers may have difficulty inhibiting or suppressing irrelevant thoughts and actions as a result of poor AC. While it has been established that suppression difficulties, due to poor AC, results in problems with the regulation of contents within WM, the nature of these deficits and their relation to reading is not well understood (De Beni & Palladino, 2000; Pimpterton & Nation, 2010).

AC is not a singular, generalized mechanism, but instead exists as a “family of functions” that work together to regulate the contents of WM (Cain, 2006; Friedman & Miyake, 2004). Response inhibition, sustained attention, and cognitive inhibition are three separable functions of AC, but it is not clear how distinct these functions are in relation to their regulation of the contents of WM (Friedman & Miyake, 2004). It is also
unclear which of these functions of AC may most significantly contribute to decoding skills versus reading comprehension ability.

**Response inhibition.** Response inhibition is the deliberate or effortful, controlled suppression of dominant, automatic, or prepotent responses to external stimuli (Logan & Cowan, 1984; Verbruggen & Logan, 2008). This process results in the sudden and complete stopping of an individual’s planned or ongoing actions at the point in which these actions become inappropriate, as a result of a change in the immediate environment (Williams, Ponessse, Schachar, Logan, & Tannock, 1999). Logan and Cowan’s (1984) “horserace” model indicates that response inhibition is the result of an internal race between excitatory go processes and inhibitory stop processes, in response to an external stimulus. Successful inhibition occurs when the controlled stop process responds to the stimulus before the prepotent go process has had the opportunity to do so. Unsuccessful inhibition may result in the occurrence of an undesired action because the stop process fails to engage before the go process has been completed.

Response inhibition has most frequently been studied in individuals who suffer from AC deficits, such as students with attention-deficit hyperactivity disorder (ADHD; Lipszyc & Schachar, 2010). Individuals with ADHD have been shown to exhibit both poor response inhibition skills as well as reading difficulties (Castellanos & Tannock, 2002; Epstein, Johnson, Varia, & Connors, 2001; Lipszyc & Schachar, 2010; Schachar et al., 2000). Students with ADHD have also demonstrated poor WM skills (de Jong et al., 2009; Stevens, Quittner, Zuckerman, & Moore, 2002; Van De Voorde et al., 2010; Van De Voorde, Roeyers, Verte, & Wiersema, 2011).
Previous research has indicated that response inhibition and WM deficits are evident in students with poor decoding skills, similar to those seen in students with ADHD (de Jong et al., 2009; Purvis & Tannock, 2000; Stevens et al., 2002). These results may indicate that poor response inhibition contributes to the WM deficits evident in both ADHD and poor word reading skills. Barkley (1997) suggested that response inhibition and WM are positively correlated and thus, those who are better able to inhibit inappropriate responses should also be more proficient in processing and storing information which is being read. This should indicate that those students who exhibit good response inhibition skills should also perform well on WM tasks. Additionally, it would suggest that response inhibition would be positively correlated with reading ability. Despite this, the relation between response inhibition and reading comprehension has not been clearly established.

The Stop-Signal task is a well validated measure of response inhibition and has frequently been used to assess response inhibition in students with reading difficulties as well as those with ADHD (de Jong et al., 2009; Flory et al., 2006; Purvis & Tannock, 2000; Schachar & Logan, 1990; Stevens et al., 2002; Verbruggen & Logan, 2008). On go – no go tasks such as Stop - Signal, participants are instructed to respond as quickly but as accurately as possible to the ‘go’ signal in the primary task, while at the same time attempting to inhibit their response to the go signal when a concurrent ‘stop’ signal is randomly presented 25% of the time (Schachar & Logan, 1990). Students with reading difficulties associated with poor decoding skills have been shown to have reduced response inhibition skills as indicated by longer stop signal reaction times (SSRTs) on the Stop – Signal task (de Jong et al., 2009; Purvis & Tannock, 2000). de Jong et al. (2009)
found that those children with reading disabilities attributed to poor decoding skills had significantly longer SSRTs, as compared to normal controls, indicating deficits in response inhibition. Additional studies have also shown that students with poor word reading skills perform significantly poorer on other measures of response inhibition (Locascio et al., 2010; Savage, Cornish, Manly, & Hollis, 2006; van der Schoot, Licht, Horsley, & Sergeant, 2000; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005).

Conversely, studies examining the relation between response inhibition and reading comprehension do not indicate a significant relation between the two (Alloway et al.; 2010; Christopher et al., 2012; Locascio et al., 2010). Locascio et al. (2010) found that typically developing children and children with reading comprehension difficulties not associated with poor word reading do not differ in response inhibition skills. Using the Stop – Signal task, Flory et al. (2006) found that response inhibition did not predict online story comprehension in poor comprehenders. Together, these results may indicate that response inhibition skills play a role in word reading skills but not necessarily reading comprehension abilities not associated with decoding skills. This distinction may be partially attributed to the relation of response inhibition to WM, which has been shown to function differently in reading comprehension and decoding ability (Catts et al., 2006; Christopher et al., 2012; Seigneuric & Ehrlich, 2005).

**Sustained attention.** Adequate reading requires sustained attention in order to maintain an active representation of the text being read. Sustained attention provides the ability to maintain attention and focus on task relevant goals over an extended period of time (Astle & Scerif, 2011). That being said, inattention does not present with a complete
lack of attention but rather an inconsistent, on-and-off pattern in which attention is not consistently directed towards the intended task (Aaron, Joshi, Palmer, Smith, & Kirby, 2002; Smallwood, Fishman, & Schooler, 2007). Behaviors such as avoidance of tasks that require sustained mental effort, difficulty organizing tasks, increased distractibility, and spontaneous mind wandering, are characteristic of deficits in sustained attention (Castellanos & Tannock, 2002; Smallwood et al., 2007; Smallwood, McSpadden, & Schooler, 2008). Students with low WM are often described by teachers as showing evidence of poor sustained attention in the classroom (Alloway, Gathercole, Kirkwood, & Elliot, 2009).

The ability to sustain attention has been shown to be closely linked to components of WM (Astle & Scerif, 2011; Savage et al., 2006). Sustained attention is important for the efficient coordination of WM resources, which in turn facilitates development of a coherent understanding of the text. Lack of attention to the task at hand limits the reader’s ability to retrieve relevant information about the text from WM (Smallwood et al., 2008). Fluctuations in attention may disrupt the reader’s capacity to process information with enough detail to develop a viable understanding of the text (Aaron et al., 2002; Flory et al., 2006; Smallwood et al., 2008). Sustained attention is needed to continuously update WM in order to maintain an active representation of information being read.

Children with poor sustained attention have been shown to present with WM deficits that negatively impact learning and reading (Alloway, Elliot, & Place, 2010). Measures of sustained attention have been shown to be significantly correlated with measures of both single word decoding and reading comprehension (Savage et al., 2006; Sesma et al., 2009). However, research indicates that poor decoding skills and deficits in
sustained attention, such as those associated with ADHD – Inattentive subtype, impact reading comprehension differently (Aaron et al., 2002). Sustained attention has been shown to significantly contribute to decoding skills, independent of phonological skills (Bosse & Valdois, 2009). Poor sustained attention has also been shown to negatively impact reading comprehension (Smallwood et al., 2008; Silva-Pereyra et al., 2010). Poor reading skills may involve an inability to sustain attention on the text therefore limiting the reader’s ability to comprehend information being read.

Flory et al. (2006) used the Stop - Signal task to assess both response inhibition and inattention in 116 school - aged children (49 with ADHD, 67 non - referred controls). Those children who showed evidence of inadequate sustained attention performed more poorly on an online story comprehension task, whereas response inhibition did not predict task performance. Additionally, interventions designed to target poor sustained attention have been shown to improve reading comprehension in poor comprehenders whose deficits do not stem from inadequate decoding abilities (Coelho, 2005; Solan, Shelley-Tremblay, Ficarra, Silverman, & Larson, 2004). These results may indicate that poor sustained attention contributes to deficits in reading comprehension that do not result from poor decoding. Poor reading comprehension may be the result of an inability to focus attention on the text, which leads to difficulties with the processing and maintenance of information in WM (Flory et al., 2006; Silva-Pereyra et al., 2010).

**Cognitive inhibition.** Cognitive inhibition is associated with the control of mental processes involved in suppressing unwanted or irrelevant thoughts and context - inappropriate meanings, as well as gating irrelevant information from WM (Friedman & Miyake, 2004). Cognitive inhibition works to resist memory intrusions from previously
relevant information once it has become no longer relevant to the task at hand. This is an active and automatic process that regulates the information within WM by resisting intrusions from previous information. Research indicates that difficulty with the suppression of irrelevant and/or distracter information is associated with poor cognitive inhibition skills (Friedman & Miyake, 2004; Gernbacher & Faust, 1991; Pimperton & Nation, 2010; White, 2007). The ability to suppress irrelevant information from WM is important for reading because it dampens context—irrelevant information that might otherwise interfere with the development of an accurate mental representation of the text (Gernbacher & Faust, 1991). The ability to inhibit irrelevant information during reading is necessary for the maintenance of a meaning—based representation that is important for a coherent understanding of the text.

When a text is read, multiple meanings can become activated within WM. Good cognitive inhibition skills help to inhibit the context—irrelevant meanings so as not to overburden WM with previously activated but no longer relevant information. As ambiguous words are processed in context, less skilled comprehenders are less able to reject irrelevant meanings over time (Gernsbacher & Faust, 1991). The more closely related an ambiguous or distracter word is to the task at hand, the more difficult it is to suppress (Cain et al., 2004; Kipp, Pope, & Digby, 1998). Poor comprehenders have been shown to recall more distracters, such as inappropriate words or context—irrelevant meanings for ambiguous words, as compared to good comprehenders (Borella, Carretti, & Pelegrina, 2010; Cain, 2006; Pimperton & Nation, 2010).

Interference from distracter information disrupts the ability to maintain a coherent representation of the text. Poor comprehenders, on average, are more likely to experience
interference from distracter information, suggesting deficits in cognitive inhibition skills. Poor comprehenders have been shown to perform significantly poorer on measures of cognitive inhibition, compared to good comprehenders (Borella et al., 2010; Cain, 2006; De Beni et al., 1998). On the other hand, poor readers whose difficulties emerge from poor word reading skills, do not differ from good readers on measures of cognitive inhibition (Chiappe, Hasher, & Siegal, 2000; Otto & Fredricks, 1963). Borella et al. (2010) found that good comprehenders outperform poor comprehenders on measures of cognitive inhibition, whereas there was no significant difference between the two groups in performance on response inhibition tasks. Students with poor reading comprehension and adequate decoding skills have also shown problems suppressing irrelevant information, suggesting that poor comprehension is related to poor cognitive inhibition, in individuals whose comprehension deficits do not arise from underlying decoding problems (Barnes, Faulkner, Wilkinson, & Dennis, 2004).

The Verbal Proactive Interference task assesses students’ cognitive inhibition skills by requiring them to recall a target word from a list of words previously heard when words that are semantically related to the target are also present. Poor comprehenders have been shown to recall a distracter word that is semantically related to the target word (an animal word, such as dog, they have been asked to forget from a previous list in order to recall cat from the current list) more often than good comprehenders on this task (Pimperton & Nation, 2010). These intrusions, evident in poor comprehenders, are interpreted to be a consequence of the poor regulation of the contents of WM that are associated with weak cognitive inhibition skills (Borella et al., 2010; De Beni & Palladino, 2000; Pimperton & Nation, 2010).
Proficient reading requires the reader to maintain and constantly update relevant information while at the same time ignoring or suppressing that information which is less important. Weak cognitive inhibition skills can lead to an interference of competing information and an overburdening of the WM system, making the development of a coherent representation more difficult (Chiappe et al., 2000; De Beni et al., 1998; Pimperton & Nation, 2010). The inability of less skilled readers to inhibit irrelevant information disrupts the maintenance of a meaning-based representation that is crucial for adequate comprehension.

Current Study

Researchers have been investigating the relation of WM and AC to reading, but much of this research has been done with those readers with poor word reading abilities (Bosse & Valdois, 2009; Chiappe et al., 2000; Purvis & Tannock, 2000; van der Sluis, de Jong, & van der Leij, 2007). Only recently have researchers begun to investigate the role of WM and AC in those students with reading comprehension abilities not associated with decoding skills (Alloway et al., 2010; Cutting et al., 2009; De Beni et al., 1998; Locascio et al., 2010; Pimperton & Nation, 2010). There is a significant relation between deficits in WM and both poor decoding skills and poor reading comprehension (Catts et al., 2006; Seigneur & Ehrlich, 2005; Sesma et al., 2009). However, what is not clear is whether WM operates differently in relation to decoding versus comprehension. In addition, the allocation of AC resources and their role in differential relations with decoding and comprehension has not been adequately studied, regardless of the level of reading ability (Catts et al., 2006; Christopher et al., 2012; Cutting et al., 2009; Locascio et al., 2010).
The purpose of the current study was to evaluate the contribution of WM and AC to reading comprehension and decoding ability. In addition, the relations of WM and each of the three AC functions of response inhibition, sustained attention, and cognitive inhibition were analyzed.

*Hypothesis 1) Working memory:* Each function of AC will be relatively independent (i.e., not redundant) and make a unique contribution to WM in accordance with its unique role in the maintenance of contents of WM. Therefore each function of AC - response inhibition, sustained attention, and cognitive inhibition – will account for unique variance in WM.

*Hypothesis 2) Reading comprehension:* Due to the unique relation of each AC function and WM, it is hypothesized that response inhibition, sustained attention, and cognitive inhibition will differ in the contribution of each function to reading comprehension. 2a) Response inhibition is important for the regulation of automatic behavior, but not necessarily the regulation of information within WM (Schachar & Logan, 1990; de Jong et al., 2009; Purvis & Tannock, 2000; van der Sluis et al., 2007; Van De Voorde et al., 2011). Therefore, it is hypothesized that response inhibition will not make a significant contribution to reading comprehension. 2b) Adequate reading comprehension requires consistent focus on the text and difficulty in sustaining attention has been shown to negatively impact reading comprehension (Bosse & Valdois, 2009; Smallwood et al., 2008). Because of this, it is hypothesized that sustained attention will be a significant predictor of reading comprehension. 2c) Cognitive inhibition is responsible for the regulation of contents within WM and is important for the revision and updating of information during reading of text (Pimperton & Nation, 2010).
Therefore, it is hypothesized that cognitive inhibition will be a significant predictor of reading comprehension.

*Hypothesis 3) Decoding versus comprehension:* While both reading comprehension and decoding skills require the use of WM, the role of WM differs in each component of reading due to the contribution of AC to WM. It is hypothesized that AC will be differentially related to decoding versus reading comprehension with response inhibition, but not sustained attention or cognitive inhibition, significantly contributing to decoding ability.

**Method**

**Participants**

One thousand seven hundred and sixty-three students in grades 6 through 12 from mainstream classrooms in schools within the greater Houston area were randomly selected and approached to participate in the study. Students who consented were screened on letter-word knowledge and general intelligence. Students who scored at or above the 20th percentile on the *Woodcock-Johnson III* (WJ-III) *Tests of Achievement*, Letter Word Identification subtest (Woodcock, McGrew, & Mather, 2001) and had a verbal and/or fluid intelligence score at or above 70, as determined by the *Kaufman Brief Intelligence Test – 2* (K-BIT-2; Kaufman & Kaufman, 2004) were eligible to continue the study. In total, 166 students refused consent, and 411 students were disqualified due to poor letter-word knowledge. Students who passed the screening measures were then tested on a larger assessment battery. Those who successfully completed all relevant portions of the battery took part in this study. In total, 1134 adolescent students (588
male, 546 female) qualified, successfully completed the relevant tasks, and were included for this study.

**Procedures**

As part of a larger study, each student was tested in a quiet area of the school for two or three sessions over a course of one week, based on availability. The following tasks were administered by a member of the research team in accordance with standardized task administration procedures. The *Gates – MacGinitie Reading Tests* (GMRT) Comprehension subtest was administered in a group setting (MacGinitie, MacGinitie, Maria, & Dreyer, 2000). All other tasks were administered individually.

**Measures**

**Reading comprehension.** The GMRT Comprehension subtest is a group–administered assessment of reading comprehension (MacGinitie et al., 2000). The task requires participants to read a passage of text silently and answer relevant comprehension questions within a 35 minute time limit. Internal consistency reliability ranges from .91 to .93. Lexile scores derived from performance on the task were used in analyses as a measure of reading comprehension. The lexile score is derived from a Rasch equation which uses the sentence length and word frequency associated with the correctly read text to provide an objective measure of reading comprehension (Stenner, Burdick, Sanford, & Burdick, 2006).

**Decoding.** The Phonemic Decoding Efficiency and the Sight Word Reading Efficiency subtests of the *Test of Word Reading Efficiency* (TOWRE; Torgesen, Wagner, & Rashotte, 1999) were used to assess decoding ability. The TOWRE is an individually
administered assessment which measures students’ ability to read words out of context. It consists of two timed measures of real-word reading, which measures students’ ability to quickly recognize common words, and pseudoword decoding, which measures students’ ability to sound out words quickly and accurately. The internal consistency for both tests exceeds .95. A composite score, combining the calculated scores of each subtest was used as a measure of decoding ability, which reflects accuracy within a 45-second time limit on each subtest.

**Working memory.** Working memory was assessed using the Numbers Reversed subtest of the *WJ-III Tests of Cognitive Abilities* (Woodcock et al., 2001). The WJ-III Numbers Reversed subtest is part of a nationally standardized, individually administered battery of achievement tests with excellent psychometric properties and internal consistency exceeding .90. In this task students are required to immediately recall a string of digits presented orally by the examiner and repeat them back in reverse order. The task begins with a set of trials consisting of a string of three digits each. Additional trials continue with strings getting progressively longer with each set of successful trials. The task is discontinued when the student responds incorrectly to three successive trials. The number of trials correct is used to produce a measure of WM (Woodcock et al., 2001).

**Response inhibition and sustained attention.** Response inhibition and sustained attention were measured using the Stop Signal paradigm, a computerized choice reaction-time task (Schachar & Logan, 1990). Students completed one practice block and four test blocks that consisted of 24 trials per block. Students were instructed to respond, via the game controller, as quickly but as accurately as possible to the ‘go’ signal in the primary
task. The go signal task consists of a completely randomized series of ‘X’s or ‘O’s that appear on the computer screen. During the ‘stop’ task, an audible tone is presented after the go stimulus appears on the screen. The stop signal prompts the student to attempt to not respond to the go signal of that trial.

Timing of the stop task presentation is adaptive based on the independent horse-race model developed by Logan (1981). The sequence of presentation of stop and go signal tasks are completely random per trial and is adaptive to ensure the student is accurate on stop signal trials 50% of the time with the stop signal appearing 25% of all trials (6 trials per block). Response inhibition scores were derived using the SSRT score, stop-signal delay minus mean go reaction time (Schachar & Logan, 1990). A measure of inattention was obtained by standardizing and combining the standard deviation of reaction times to all go signals and the number of go signals not responded to (omission errors; Flory et al., 2006).

**Cognitive inhibition.** The computerized Verbal Proactive Interference (VPI) task was used to assess cognitive inhibition (Pimperton & Nation, 2010). The task is comprised of 4 practice trials and 24 test trials, each of which consists of either a single or double block structure. Eight single block trials were included to ensure that students paid attention to the first set of words, in addition to the second set in the 16 double block trials. Each trial begins with the visual prompt ‘Ready?’ that is followed directly by an audible list of four stimulus words. In the single block trial, the list of words is followed by the appearance of a question mark (?) on the screen. During the double block, the list of words is followed by the appearance of an ‘X’ on the screen and then the presentation of an additional list of four words. The appearance of an ‘X’ on the screen indicated to
students that they were to forget the first list of four words and instead focus on remembering the second list of four words. In both the single and double block trials, directly following the completion of the final word list and appearance of the question mark, students were required to shadow a list of 20 numbers, presented verbally by the examiner, to prevent rehearsal. Immediately after shadowing, students were asked to recall a word from the list in response to a category cue (e.g. Can you remember the word that was a type of pet?).

Exactly half of the 16 double block trials consisted of ‘inference’ trials, while the other half were ‘no-interference’ trials. In the no-interference trials, a word matching the category cue (e.g. type of pet) is present in the second block of words only (with the target word, dog). In the interference trials both the first list (with the foil word, cat) and the second list (with the target word, dog) contained a category cue matching word. Students’ responses were scored as correct if the student was able to successfully produce the target word. A measure of cognitive inhibition was provided by the number of interference trials correctly responded to (Pimperton & Nation, 2010). The number of no-inference trials correctly responded to provided a measure of verbal short term memory.

**Data Analyses**

In order to test hypothesis 1, multiple regression analyses were used to examine the relative contribution of the three measures of AC to the prediction of calculated totals on the WJ – III Numbers Reversed subtest as a measure of WM. Hierarchical multiple regression analyses of age (as determined by grade level) with measures of WM, verbal short term memory, response inhibition, sustained attention, and cognitive inhibition to the prediction of GMRT lexile scores as a measure of reading comprehension were
performed to test hypothesis 2. The same model was also applied to the predication of scores on the TOWRE decoding composite in order to test hypothesis 3 and assess whether measures of WM and AC differentially predicted performance on measures of reading comprehension and of decoding.

Results

Relations with Grade

Descriptive statistics for WM and each AC variable, as well as reading comprehension and decoding measures of interest are summarized by grade in Table 1. Mean scores for each of the tasks were broadly within expected range. Analysis of variance of each measure indicated significant effects of grade for all measures \((p < .001)\), with the exception of Stop Signal Inattention. Follow up Tukey’s tests were then conducted to identify significant differences between each grade level \((p < .05)\).

Table 1 Descriptive Statistics for All Variables by Grade

<table>
<thead>
<tr>
<th>Variable</th>
<th>6 (n=116)</th>
<th>7 (n=163)</th>
<th>8 (n=173)</th>
<th>9 (n=177)</th>
<th>10 (n=192)</th>
<th>11 (n=177)</th>
<th>12 (n=136)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMRT Lexile</td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td></td>
<td>(SD)</td>
<td>(SD)</td>
<td>(SD)</td>
<td>(SD)</td>
<td>(SD)</td>
<td>(SD)</td>
<td>(SD)</td>
</tr>
<tr>
<td>GMRT Lexile</td>
<td>775.52a</td>
<td>784.69a</td>
<td>852.02b</td>
<td>878.93b</td>
<td>996.51c</td>
<td>983.16c</td>
<td>1016.40c</td>
</tr>
<tr>
<td></td>
<td>(160.65)</td>
<td>(164.80)</td>
<td>(132.73)</td>
<td>(182.65)</td>
<td>(140.68)</td>
<td>(143.42)</td>
<td>(160.65)</td>
</tr>
<tr>
<td>TOWRE Decoding</td>
<td>102.78a</td>
<td>98.22ab</td>
<td>95.50bc</td>
<td>94.51bc</td>
<td>92.53c</td>
<td>90.28d</td>
<td>87.66d</td>
</tr>
<tr>
<td>WJIII Numbers</td>
<td>12.67ace</td>
<td>12.42a</td>
<td>13.70a</td>
<td>13.70ab</td>
<td>13.68ab</td>
<td>13.70abc</td>
<td>14.19b</td>
</tr>
<tr>
<td>Reversed</td>
<td>(92.55)</td>
<td>(3.10)</td>
<td>(3.50)</td>
<td>(3.50)</td>
<td>(2.99)</td>
<td>(3.67)</td>
<td>(3.37)</td>
</tr>
<tr>
<td>Stop Signal SSRT</td>
<td>317.98a</td>
<td>306.38ab</td>
<td>281.58ab</td>
<td>278.87bc</td>
<td>278.87bc</td>
<td>275.97c</td>
<td>275.31b</td>
</tr>
<tr>
<td></td>
<td>(83.15)</td>
<td>(84.79)</td>
<td>(93.70)</td>
<td>(93.70)</td>
<td>(108.29c)</td>
<td>(108.29)</td>
<td>(99.94)</td>
</tr>
<tr>
<td>Stop Signal Inattention</td>
<td>183.25a</td>
<td>180.74a</td>
<td>176.79a</td>
<td>173.79a</td>
<td>173.79a</td>
<td>180.37a</td>
<td>184.72a</td>
</tr>
<tr>
<td></td>
<td>(48.67)</td>
<td>(46.19)</td>
<td>(46.89)</td>
<td>(46.81)</td>
<td>(46.81)</td>
<td>(48.73)</td>
<td>(46.61)</td>
</tr>
<tr>
<td>VPI No Interference</td>
<td>5.32a</td>
<td>5.27a</td>
<td>5.49abc</td>
<td>5.75abc</td>
<td>5.92cd</td>
<td>5.94cd</td>
<td>6.04d</td>
</tr>
<tr>
<td>Trials</td>
<td>(1.59)</td>
<td>(1.59)</td>
<td>(1.49)</td>
<td>(1.35)</td>
<td>(1.40)</td>
<td>(1.35)</td>
<td>(1.46)</td>
</tr>
<tr>
<td>VPI Interference Trials</td>
<td>3.75a</td>
<td>3.88ab</td>
<td>4.13a</td>
<td>4.39bce</td>
<td>4.39bce</td>
<td>4.22ace</td>
<td>4.71c</td>
</tr>
<tr>
<td></td>
<td>(1.39)</td>
<td>(1.56)</td>
<td>(1.81)</td>
<td>(1.70)</td>
<td>(1.70)</td>
<td>(1.65)</td>
<td>(1.83)</td>
</tr>
</tbody>
</table>
Relations of Attentional Control, Working Memory, and Reading

The zero-order relations between performance on the GMRT Comprehension subtest, TOWRE decoding composite score, WJ-III Numbers Reversed subtest, and performance on tasks measuring AC functions thought to be involved in the regulation of WM were examined using Pearson’s correlation coefficients, reported in Table 2. As expected, the GMRT Comprehension subtest lexile score was positively correlated with the TOWRE decoding composite score, \( r = .48 \) \( p < .0001 \). Measures of reading comprehension and decoding were also positively correlated with performance on the WJ – III Numbers Reversed subtest at \( r = .32, p < .0001 \), and \( r = .22, p < .0001 \), respectively. The Stop Signal measures of response inhibition (SSRT) and sustained attention (Inattention) had a weak, negative correlation with performance on the WJ-III Numbers Reversed subtest, \( r = -.06, p = .05 \) and \( r = -.07, p = .01 \). The VPI measure of cognitive inhibition (calculated total of correct interference trials) was positively correlated at \( r = .22, p < .0001 \), with performance on the measure of WM. The three measures of AC were not significantly correlated with one another. These results support hypothesis 1 in that each function of AC is correlated with WM but not the other functions of AC.

Scores on measures of WM and AC were significantly related to performance on the GMRT Comprehension subtest, with absolute values of correlation coefficients ranging from \( r = .09 \) to \( r = .32, p < .01 \). Performance on the measure of cognitive inhibition, VPI calculated total of correct interference trials, was positively correlated
with reading comprehension, with higher scores predicting better performance on the GMRT Comprehension subtest. Stop Signal measures of response inhibition and inattention were negatively correlated with reading comprehension, such that poorer reading comprehension was associated with higher scores on these measures.

Table 2 Intercorrelations Among Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Grade</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. TOWRE Decoding</td>
<td>-0.28†</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. GMRT Lexile</td>
<td>.48†</td>
<td>.11**</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. WJIII Numbers Reversed</td>
<td>.17†</td>
<td>.22†</td>
<td>.32†</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Stop Signal SSRT</td>
<td>-0.14†</td>
<td>-0.07*</td>
<td>-0.12†</td>
<td>-0.06*</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Stop Signal Inattention</td>
<td>-0.001</td>
<td>-0.03</td>
<td>-0.09**</td>
<td>-0.07**</td>
<td>0.03</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. VPI No Interference Trials</td>
<td>.18†</td>
<td>.06*</td>
<td>.29†</td>
<td>.17†</td>
<td>-0.04</td>
<td>-0.06*</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>8. VPI Interference Trials</td>
<td>.15†</td>
<td>.03</td>
<td>.22†</td>
<td>.22†</td>
<td>-0.03</td>
<td>-0.03</td>
<td>.33†</td>
<td>--</td>
</tr>
</tbody>
</table>

* Significant at p < .05 **Significant at p < .01 †Significant at p < .001

Working memory

Having established small, but statistically significant correlations between each of the three functions of AC and scores on the WJ - III Numbers Reversed subtest as a measure of WM, as well as a lack of redundancy in each of the AC measures, the contribution of each function of AC to WM was evaluated using a series of regression analyses. In order to further test hypothesis 1, three separate regression models were used to assess the contribution of each AC function to WM. Grade was also included in these models in order to control for age-related differences in WM. The dependent variable was the calculated total on the WJ - III Numbers Reversed subtest.

Model 1 consisted of grade and Stop Signal SSRT and significantly predicted WM, $F(1, 1129) = 18.45, p < .0001$. Despite the model achieving statistical significance, Stop Signal SSRT was not a significant predictor in the model, indicating that response
inhibition, as measured by Stop Signal SSRT, does not account for unique variance in WM.

Model 2 consisted of grade and Stop Signal Inattention predicting WM. This model was significantly related to WM, $F(1,1129) = 20.67, p < .0001$. Both grade and Stop Signal Inattention were significant predictors in the model, with an associated adjusted $R^2 = .03$.

Model 3 included grade and calculated total of correct interference trials on the VPI task predicting WM. The calculated total of correct no-interference trials on the VPI task was also included in the model in order to account for the verbal short-term memory component of the task. This model was significant, $F(3, 1126) = 31.11, p < .0001$. The model had an associated adjusted $R^2 = .07$. Correct interference trials was a significant predictor in the model, indicating that cognitive inhibition accounted for unique variance in WM.

A full hierarchical regression model consisting of grade and each of the three functions of AC as predictors was then used to assess the unique contribution of each function of AC to WM. The hierarchical regression model included the following variables, in order of entry: 1) grade, 2) calculated total of correct no-interference trials on the VPI task 3) Stop Signal SSRT, 3) Stop Signal Inattention, and 5) the calculated total of correct interference trials on the VPI task. Table 3 reports the results of the hierarchical regression analysis. The full model significantly predicted WM, $F(5,1124) = 19.62, p < .0001$. Stop Signal Inattention and VPI correct interference trials, as well as grade and VPI no-interference trials, each made a unique contribution to WM, indicating that improved performance on these measures predicts performance on the WJ - III
Numbers Reversed subtest. Stop Signal SSRT was not a significant predictor in the model. The adjusted $R^2$ associated with this model was .08. These results partially support hypothesis 1, indicating that the AC functions of sustained attention and cognitive inhibition account for a significant amount of unique variance in WM.

**Table 3 Hierarchical Multiple Regression Analysis Predicting Working Memory**

| Step & Predictor                   | Parameter Estimate | Standard Error | $t$ value | Pr > |t| |
|-----------------------------------|--------------------|----------------|-----------|------|---|
| Grade                             | .22                | .05            | 4.34      | < .0001 |
| VPI No Interference Trials       | .18                | .07            | 2.65      | .008 |
| Stop Signal SSRT                  | -0.0009            | .0001          | -0.91     | .36  |
| Stop Signal Inattention           | -0.004             | .002           | -1.91     | .05  |
| VPI Interference Trials          | .34                | .06            | 5.76      | <0.0001 |

*Full Model Predicting WM: Adjusted $R^2$ at final step = .08; $F(5, 1124) = 19.62, p <0.0001*

**Reading Comprehension**

In order to test hypothesis 2, each variable’s relative contribution to reading comprehension was evaluated using a series of hierarchical multiple regression analyses. Each model also included grade in order to control for age-related differences in reading comprehension. The dependent variable was the numeric lexile score from the GMRT Comprehension subtest. An initial model consisting of grade and WM was used to assess the contribution of age and WM to reading comprehension. This model was significant at $F(2, 1129) = 233.64, p < .0001$, with an adjusted $R^2 = .29$.

After confirming a significant contribution of WM to reading comprehension, three separate three-predictor models were used to assess the contribution of WM and each function of AC to reading comprehension. Model 1 consisted of grade, WM, and response inhibition predicting reading comprehension. The overall model was
significantly related to reading comprehension, $F(3, 1128) = 156.83, p < .0001$ but the predictor of Stop Signal SSRT as a measure of response inhibition was not significant, indicating that response inhibition does not account for unique variance in reading comprehension after accounting for grade and WM performance.

Model 2, consisting of grade, WM, and sustained attention significantly predicted reading comprehension, $F(3, 1128) = 160.07, p < .0001$. The Stop Signal Inattention measure was a significant predictor in the model.

Model 3, consisting of grade, WM, verbal short-term memory, and cognitive inhibition predicting reading comprehension was also significant, $F(4, 1125) = 134.09, p < .0001$. Calculated total of interference trials from the VPI task, as a measure of cognitive inhibition, was a significant predictor of reading comprehension in the model.

The full hierarchical regression model included the following variables in order of entry: 1) grade, 2) the calculated total score from the WJ-III Numbers Reversed subtest, 3) the calculated total of correct no-interference trials from the VPI task 4) Stop Signal SSRT, 5) Stop Signal Inattention, and 6) calculated total for correct interference trials from the VPI task. Table 4 reports the results of the hierarchical regression analysis. The full model significantly predicted reading comprehension, $F(6,1123) = 91.59, p < .0001$. After accounting for grade, short-term memory, and WM performance, sustained attention and cognitive inhibition each made a unique contribution to reading comprehension, indicating that improved performance on these measures predicts reading comprehension. Response inhibition was not a significant predictor in the model. The adjusted $R^2$ associated with this model was .33. These results support hypothesis 2,
indicating that sustained attention and cognitive inhibition, but not response inhibition, account for unique variance in reading comprehension.

**Table 4** Hierarchical Regression Analysis Predicting GMRT Lexile

| Step & Predictor                        | Parameter Estimate | Standard Error | t value | Pr > |t| |
|----------------------------------------|--------------------|----------------|---------|-------|-------|
| Grade                                  | 38.96              | 2.43           | 16.04   | <.0001|
| WJIII Numbers Reversed                 | 11.14              | 1.41           | 7.90    | <.0001|
| VPI No Interference Trials             | 18.25              | 3.19           | 5.72    | <.0001|
| Stop Signal SSRT                       | -0.067             | .05            | -1.45   | .15   |
| Stop Signal Inattention                | -0.25              | .09            | -2.69   | .007  |
| VPI Interference Trials                | 6.73               | 2.85           | 2.36    | .01   |

*Full Model Predicting Reading Comprehension:* Adjusted $R^2$ at final step = .33; $F(5, 1124) = 91.59$, $p < .0001$

**Decoding**

To test hypothesis 3, the same models were also applied to the prediction of the composite score of the TOWRE Sight Word and Phonemic Decoding subtests in order to assess whether measures of AC were related equally or differentially to performance on measures of reading comprehension and measures of decoding ability. An initial model consisting of grade and WM was used to predict TOWRE decoding. This model was significant, $F(2, 1127) = 101.76$, $p < .0001$, with both grade and WM as significant predictors in the model. The adjusted $R^2$ of the model was .15.

After establishing the significant contribution of WM to decoding, additional models were used to assess the contribution of AC to performance on the TOWRE measure of decoding. The first model, with predictors of grade, WM, and response inhibition, significantly predicted performance on the TOWRE decoding composite, $F(3, 1126) = 91.15$, $p < .0001$, with all three predictors making a significant contribution to decoding ability. Models 2 and 3 were also significant, $F(3, 1126) = 85.09$, $p < .0001$.
and $F(4, 1123) = 53.44, p < .0001$ respectively, but neither sustained attention nor
cognitive inhibition served as significant predictors of decoding.

Results of the hierarchical regression analysis of the full model, reported in Table 5, indicated that the full model was significant in predicting performance on the TOWRE decoding composite, $F(6, 1121) = 28.07, p < .0001$. Results indicated that grade, verbal short–term memory, WM, and response inhibition significantly contributed to the prediction of higher scores on the measure of decoding. However, sustained attention and cognitive inhibition did not contribute significantly to the prediction of performance on the TOWRE decoding measure. The adjusted $R^2$ for this model was .16. These results support hypothesis 3 in that AC differentially contributes to reading comprehension and decoding, with response inhibition accounting for unique variance in decoding.

Table 5 Hierarchical Regression Analysis Predicting TOWRE Decoding

<table>
<thead>
<tr>
<th>Step &amp; Predictor</th>
<th>Parameter Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>Pr &gt;</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>-2.28</td>
<td>.18</td>
<td>-12.58</td>
<td>&lt;.0001</td>
<td></td>
</tr>
<tr>
<td>WJIII Numbers Reversed</td>
<td>.97</td>
<td>.10</td>
<td>9.23</td>
<td>&lt;.0001</td>
<td></td>
</tr>
<tr>
<td>VPI No Interference Trials</td>
<td>.68</td>
<td>.24</td>
<td>2.88</td>
<td>.004</td>
<td></td>
</tr>
<tr>
<td>Stop Signal SSRT</td>
<td>-0.01</td>
<td>.003</td>
<td>-3.54</td>
<td>.0004</td>
<td></td>
</tr>
<tr>
<td>Stop Signal Inattention</td>
<td>-0.001</td>
<td>.007</td>
<td>-0.20</td>
<td>.83</td>
<td></td>
</tr>
<tr>
<td>VPI Interference Trials</td>
<td>-0.08</td>
<td>.21</td>
<td>-0.38</td>
<td>.71</td>
<td></td>
</tr>
</tbody>
</table>

*Full Model Predicting Phonemic Decoding: Adjusted $R^2$ at final step = .16; $F(6, 1124) = 38.07, p < .0001*

Discussion

Many students who experience reading comprehension deficits do so because of underlying poor decoding skills. However, there are also students who experience poor reading comprehension, despite adequately developing decoding skills. The current study sought to examine the unique contribution of three functions of AC - response inhibition, sustained attention, and cognitive inhibition - to WM. It also examined the contribution
of the three functions of AC and WM to reading comprehension and decoding. Previous research indicates that WM and AC may contribute differently to reading comprehension and decoding skills (Catts et al., 2006; Locascio et al., 2010; Sesma et al., 2008).

**Attentional Control and Working Memory**

I hypothesized that each function of AC would differentially contribute to WM performance. The results of this study supported this hypothesis, as each function of AC was significantly correlated with performance on a measure of WM while also lacking any significant correlations between the other measures of AC. Results of a hierarchical multiple regression analysis additionally supported this hypothesis and indicated that sustained attention and cognitive inhibition, but not response inhibition, each accounted for unique variance in WM. These results are in line with previous evidence which supports the presence of a family of AC functions, rather than a single unitary construct, with each function contributing differently to the maintenance and updating of the contents of WM (Friedman & Miyake, 2004; Nigg, 2000).

I also hypothesized that AC would contribute differently to reading comprehension and decoding ability due to the unique relation of each function of AC to WM. Taken together, the results of this study support this hypothesis, indicating that response inhibition significantly contributes to decoding ability while sustained attention and cognitive inhibition are significantly related to reading comprehension. These findings are consistent with previous research indicating that WM and AC contribute differently to reading comprehension versus decoding ability (Christopher et al., 2012; Locascio et al., 2012; Sesma et al., 2009). These findings also support previous research
suggesting that cognitive inhibition, but not response inhibition, is significantly related to reading comprehension (Borella et al., 2010; van der Sluis et al., 2004). Results of the current study suggest that this could be the result of the differing relation between each function of AC and WM.

**Role in Reading Comprehension**

Previous research indicates that cognitive inhibition is significantly related to reading comprehension, suggesting that reading comprehension requires the suppression of information that is activated in WM, in order that irrelevant information will not enter into and overwhelm WM (Borella et al., 2010; Nigg, 2000). On the other hand, reading comprehension is not as strongly associated with the need for the inhibition of preponent responses, indicating that response inhibition is may not be as strongly related to the high demand placed on WM by reading comprehension (Borella et al., 2010; Christopher et al., 2012). This is consistent with the current results that indicate that response inhibition was not significantly related to reading comprehension nor to WM. While Christopher et al. (2012) found that WM was significantly related to both reading comprehension and decoding, results of the current study suggest that a differing relation of AC to WM could differentially impact the relation of WM to decoding and reading comprehension.

Reading comprehension places a heavy demand on WM, requiring that WM be continually updated in order to maintain an active representation of the text (Sesma et al., 2009; Swanson, 1999). In the Landscape Model of Reading, the information being read (i.e. ideas and concepts) fluctuates in activation, creating a dynamic representation of the text (van den Broek, Young, Tzeng, & Linderholm, 1999; Linderholm, Virtue, Tzeng, &
van den Broek, 2004). The reader uses text being read, as well as previously read information and background knowledge, to maintain and update an accurate representation in WM. As new input from text and previously held information interact, it results in a coherent (yet constantly changing) representation. This process depends on the efficient regulation of the contents of WM.

Updating and maintenance of WM requires adequate sustained attention to ensure that focus is maintained on the task at hand, or more specifically context – relevant information, so as not to overtax WM with distracter information. It also requires the use of efficient cognitive inhibition skills in order that WM will not become overwhelmed with no longer relevant information. In the Structure – Building Framework model of reading comprehension, suppression is identified as the mechanism that works to dampen irrelevant or inappropriate meanings of text (Gernsbacher, 1996). As text is read, related information, such as irrelevant meanings of ambiguous words, can become activated in WM. The mechanism of suppression acts to resist intrusion of the irrelevant information. It is adequate cognitive inhibition skills that is related to the ability to ensure that the irrelevant (or no longer relevant) information is suppressed and WM is not overburdened. Both cognitive inhibition and sustained attention are related to the regulation of the contents of WM and facilitation of successful reading comprehension.

This relation of cognitive inhibition and sustained attention to reading comprehension, through the role of AC in the maintenance of WM, is supported by the results of the current study. Cognitive inhibition and sustained attention both accounted for unique variance in WM performance, while also uniquely predicting reading comprehension, even after accounting for age, short – term memory, WM, and the other
functions of AC. This indicates that AC is more strongly associated with reading comprehension when it comes to those functions which are related to the ability to control the current relevance of items in WM (i.e. cognitive inhibition and sustained attention). This finding is consistent with previous research examining the role of WM in reading comprehension (Borella et al., 2010; Carretti, Borella, Cornoldi, & De Beni, 2009).

**Role in Decoding**

Previous research has also shown that, like reading comprehension, decoding skills are significantly related to WM (Christopher et al., 2012; Cohen-Mimran & Sapir, 2007; Swanson, 2010; Swanson et al., 2009). Results of the current study suggest that the relation between AC and WM may function differently in reading comprehension and decoding. The results indicated that while WM was significantly related to both reading comprehension and decoding, AC was differentially related, with only response inhibition accounting for unique variance in performance on the measure of decoding. This supports previous findings which reported that decoding is more strongly associated than comprehension with response inhibition (de Jong et al., 2009; Locascio et al., 2010).

Most previous studies that documented a relation between response inhibition and decoding used groups identified with poor decoding and/or with ADHD, a developmental disorder commonly characterized by deficits in response inhibition (Lipszyc & Schachar, 2010; Purvis & Tannock, 2000; Van De Voorde et al., 2010). Attempts to dissociate these two commonly co-occurring disorders based on response inhibition skills have typically been unsuccessful because of response inhibition deficits that are evident in both groups,
although more pronounced in children with both ADHD and reading disabilities.

Response inhibition may be important in understanding the role of WM in decoding ability. The results of the current study indicate that decoding is not as strongly associated with cognitive inhibition and sustained attention. Response inhibition was not significantly related to WM, indicating that response inhibition does not function in the regulation of the contents within WM.

Alternatively, response inhibition could be related to the inhibition of preponent responses to information that is activated during the course of reading. In the case of decoding response inhibition could be related to the inhibition of words that are orthographically similar to the word being read. When a word is read, neighboring words (those that are orthographically similar) can become temporarily activated (Seidenberg, Waters, & Barnes, 1984). Response inhibition may be responsible for inhibiting incorrect neighboring words, particularly in the case of those words that are low frequency and thus are more difficult to decode. Results of the current study suggest that response inhibition may be related to the ability to adequately inhibit the response to orthographically similar words before they enter into WM for further processing.

Additionally, previous research has suggested that the significant relation between decoding and response inhibition may lie in the shared variance of response inhibition and processing speed, which may also be related to decoding ability (de Jong et al., 2009; Purvis & Tannock, 2000; van der Sluis et al., 2007). Christopher et al. (2012) found that processing speed accounted for unique variance in word reading, but not reading comprehension, after accounting for WM and response inhibition. In addition, processing speed accounts for shared variance in various comorbid relations of reading disability,
math disability, and ADHD (Willcutt et al., 2010; in press). The Stop Signal task requires the rapid processing of visual stimuli, thus it is possible that the relation between SSRT and decoding may reside with an underlying relation to processing speed. On the other hand, a confirmatory factor analysis has shown SSRT and measures of processing speed to load on differing construct factors, indicating a lack of redundancy (Christopher et al., 2012). Further research should be used to examine the relation of measures of processing speed and response inhibition and their relation to decoding.

**Implications and Future Directions**

Understanding the differential role of WM in decoding and comprehension may lie in the role of AC in the regulation of WM. Swanson (1993, 1999) identified both central executive and phonological processing elements of Baddley’s (1992) model of WM as key components of reading comprehension. Students with reading comprehension deficits resulting from poor decoding skills showed significant deficits in both reading comprehension and executive functioning that could not be accounted for by long-term memory, phonological processing skills, or WM capacity. Swanson (1999) suggested that the reading comprehension deficits of these poor decoders could be the result of poor allocation of AC resources. The results of the current study indicate AC is differentially, but significantly related to both comprehension and decoding. This suggests that the poor allocation of AC resources could negatively impact comprehension as well as decoding.

The results of the current study have implications for the design of future interventions, specifically those targeting children with reading comprehension deficits not associated with poor decoding skills. Interventions designed to target WM and AC
have previously been implemented in an attempt to improve reading ability (Coelho, 2005; Dahlin, 2011; Dion, Roux, Landry, Fuchs, Wehby, & Dupere, 2011; Morrison & Chein, 2011; Solan et al., 2004). WM training has been shown to improve performance on a variety of cognitive tasks including measures of cognitive control, arithmetic calculation skills, and reading comprehension (Morrison & Chein, 2011). Dahlin (2011) found that a five week, computerized intervention, designed to improve visuo-spatial and verbal WM, also significantly improved reading comprehension, but not decoding skills, in students in a special education program. This could indicate that improving WM in poor comprehenders could be beneficial in promoting improved reading comprehension.

Conversely, a meta-analysis conducted by Melby – Lervag and Hulme (2012) found that WM training improved WM performance but provided no significant improvements in other cognitive abilities (i.e., verbal ability, arithmetic, decoding, or reading comprehension). A computer-based WM training program, similar to the one implemented by Dahlin (2011), was used to improve WM in students shown to have low WM that hindered academic success (Homes, Gathercole, & Dunning, 2009). While results showed improvement on WM tasks, no significant improvements were seen on measures of basic word reading or mathematical reasoning.

Identifying and targeting deficits in WM alone may not provide the best means for improving reading comprehension. Johnson and Swanson (2011) found that there were no significant differences in WM in those students who responded to a reading intervention and those who did not. However, in the same study, nonresponders had significantly lower scores on measures of AC as compared to those students considered
to be high responders. This would suggest that differences in AC could predict the degree to which a student may respond to reading interventions. If this is the case, interventions designed to target specific AC deficits could be beneficial for those students who would be least likely to respond to typical reading comprehension interventions, as was the case in Solan et al. (2004). Specifically, poor comprehenders could most benefit from training that develops sustained attention and/or cognitive inhibition, in order that they would become more efficient in regulating information in WM. On the other hand, research suggests that response inhibition is not as strongly associated with reading comprehension therefore interventions targeting this function of AC are unlikely to be effective at improving reading comprehension. Interventions aimed at improving response inhibition may, however, be beneficial for those students whose reading deficits stem for poor decoding skills, as research indicates a stronger relation between response inhibition and decoding ability. Understanding the relation between AC and WM in reading comprehension versus decoding has the potential to provide useful knowledge for the implementation of more specifically targeted reading interventions.

**Limitations**

Limitations of the current study include the use of only one task to assess each function of AC. Ideally, each function would be measured by multiple tasks designed to assess the same construct. Future studies would benefit from the use of multiple AC measures to assess each function. The use of multiple tasks per construct would allow for the use of a confirmatory factor analysis to verify the existence of three distinct function of AC. Relatedly, it is important to note that further research is needed on the extent to which WM tasks, particularly verbal WM tasks such as the one used in the current study,
relate to reading comprehension. The literature on whether reading comprehension and other measures of WM, such as visual WM, is mixed (Carretti et al., 2009; Pimperton & Nation, 2010; Sesma et al., 2009; Swanson, 1999). Research supports a strong relation between verbal WM and reading comprehension but there is also evidence indicating that other types of WM, such as visuo-spatial WM, may be related to reading comprehension as well (Carretti et al., 2009; Nation, Adams, Claudine, Bowyer – Crane, & Snowling, 1999; Swanson et al., 2009). Developing a better understanding of the relation of different types of WM to reading comprehension could be beneficial in further understanding the relation of AC to WM and its relation to reading comprehension and decoding.

It should also be noted that the results of the current study has high statistical power due to a large sample size. Being highly powered allows for significant findings of small effect sizes, therefore the relations detected in the current study are relatively small. The findings of the current study are promising but should be interpreted with caution. Additional research is needed to confirm and further expand upon the distinct relation between AC and reading comprehension versus decoding.

**Conclusion**

Reading comprehension is a task that is inherently more complex than decoding, requiring the construction and maintenance of a meaningful representation of the text in WM. It requires the successful coordination of cognitive processes involved in maintaining and updating WM, as well as those associated with the integration of information and extraction of meaning. Therefore, it is not surprising that reading...
comprehension would be associated with adequate sustained attention and cognitive inhibition, AC functions related to the maintenance of relevant information in WM as well as resistance from irrelevant distractions. On the other hand, WM resources seem to function differently in decoding, with response inhibition, an AC function associated with the ability to inhibit preponent responses, being more strongly related to decoding.
References


dysfunction among children with reading comprehension deficits. *Journal of

response. In J. Long, A.D. Baddeley (Ed.), *Attention and Performance IX* (pp.


of working memory impairments in children with attention-deficit/hyperactivity
disorder. *Journal of American Academy of Child and Adolescent Psychiatry,

meta analytic review. *Developmental Psychology*, Advance online publication.
doi:10.1037/a0028228

promise and challenges of enhancing cognition by training working memory.

*Journal of Experimental Child Psychology, 73*, 139-158.


*Psychological Bulletin, 126*(2), 220-246.


Silva-Pereyra, J. et al. (2010). Poor reading skills may involve a failure to focus attention. *NeuroReport, 21*, 34-38.


