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# INVESTIGATING SENSORY AND MOTOR DIFFERENCES IN VARYING FORCE OUTPUT IN YOUNG ADULTS WITH AND WITHOUT ADHD

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## ABSTRACT

The overarching goal of this work is to determine whether fingertip forces are related to tactile somatosensation in adults with and without Attention Deficit/Hyperactivity Disorder (ADHD). This work is important because it could improve our understanding of the neurobiology of ADHD. There is limited literature describing somatosensation and motor control in adults with ADHD. The current study evaluates somatosensation and force output in the thumb and index finger of the right hand.

This work is motivated by two previous investigations that used a similar visually guided force task (Neely et al., 2016; Neely et al., 2017). Specifically, it was reported that adults with ADHD produce more force than adults without ADHD. The current work extends previous work by investigating force output at seven force amplitudes in a similar visually guided force task, and somatosensory measures.

We have three hypotheses.

1) First, we expect to confirm our previous results and to find greater variability in force output at lower amplitudes.
2) Second, we hypothesize that tactile sensitivity will be correlated with error in the low amplitude, but not high amplitude, force conditions.
3) Third, we test the hypothesis that the mean force output will be correlated with somatosensory function.

Thirty-eight participants (19 ADHD), were recruited from a larger ongoing study. In the current investigation, we tested tactile sensation in the index finger, thumb, and palm regions of the right hand. To examine motor control, we tested grip strength, coordination, and visually guided grip force.

Consistent with our first hypothesis, mean force, standard deviation of force, and coefficient of variability (CoV) scaled to target amplitude. Low force amplitudes were characterized by greater variability than high force amplitudes. Force variability, and other force output variables were not correlated with quantitative sensory measurements, except for rate of force decrease. Self-reported scores of sensory experiences were positively correlated with ADHD symptomology. Somatosensory measures were not correlated with self-reported sensory measures. The results of this work suggest that these clinical somatosensory measurements are not sensitive enough to detect differences in participants with and without ADHD. Rate of force decrease in a precision grip motor task could be related to poor somatosensation.

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# Chapter 1

# INTRODUCTION

## 1.1 Overview

Attention deficit hyperactivity disorder (ADHD) is a prevalent developmental disorder characterized by symptoms of inattention, hyperactivity and impulsivity. Inattention often manifests as difficulty maintaining focus, whereas hyperactivity often presents as excessive or unnecessary motor activity such as tapping and fidgeting, and impulsivity often presents as quick actions without forethought (American Psychiatric, American Psychiatric, & Force, 2013). ADHD persists into adulthood for 65% of cases (Cherkasova, Sulla, Dalena, Pondé, & Hechtman, 2013; Mannuzza, Klein, Bessler, Malloy, & LaPadula, 1998). ADHD negatively impacts work performance and maintenance of a job, as well as academic performance, and interpersonal relationships (Murphy & Barkley, 1996). To improve outcomes for adults with ADHD we must gain a better understanding of the neurobiology of this disorder.

The majority of children with ADHD have sensory (Little, Dean, Tomchek, & Dunn, 2017; V. T. Shimizu, O. F. A. Bueno, & M. C. Miranda, 2014) and motor (Piek, Pitcher, & Hay, 1999) deficits. In studies using self-report of sensory experiences, children with ADHD report similar sensory experiences to children with autism spectrum disorder (ASD), which were elevated compared to typically developing children. Sensory features may be an area of overlap of behaviors seen in children who have ADHD or ASD (Little, Dean, Tomchek, & Dunn, 2017). In another study using self-report, children with ADHD scored lower in Sensation Seeking, Sensory Sensitivity, Low Registration, and Sensation Avoiding subscales than children without ADHD, suggesting children with ADHD have more sensory impairments than children without ADHD (V. T. Shimizu, O. F. Bueno, & M. C. Miranda, 2014). Although both studies show sensory differences in children with ADHD, they have conflicting results in which Little et al. (2017) found sensory hyper-sensitivity responses in children with ADHD but Shimizu et al. found hypo-sensitivity. Little et al. included older children in their study but Shimizu et al. had a mean age of six years old, indicating that there may be different responses depending on age.

The Movement Assessment Battery for Children (MABC) is a commonly used tool to identify motor impairments in motor performance in children and adolescents ages three to 16 (Brown & Lalor, 2009). The MABC incorporates dexterity tasks, ball tasks, and static and dynamic balance tasks. Ament and colleagues found that children with ADHD had poorer movement ability when compared to a control group (Ament et al., 2015).

Together, the sensory and motor studies involving children with ADHD suggest that sensory and motor deficits may be present in children with ADHD; however, sensory and motor function in adults with ADHD has rarely been quantitatively examined. The present work addresses this gap by conducting clinical quantitative somatosensory tests, a visually guided handgrip task, the Purdue Pegboard Task, and self-reported ADHD-related symptoms and sensory experiences. The novelty of this work is that all participants completed all sensory and motor tasks, such that we can evaluate how sensory and motor function are related in adults with and without ADHD.

The sensory and motor differences in children reported in previous studies may be linked back to the nervous system. Development of gross and fine motor skills depends on many factors, including accurate tactile and proprioceptive sensation (Cascio, 2010 ). Disorders that impact development, such as ADHD, have been associated with impairments in somatosensory discriminative abilities, and effective responses to tactile stimulation (Cascio, 2010 ).

**1.2 Nervous System**

The sensory and motor systems are an integral part of the human central nervous system. Specifically, the nervous system processes sensory information and uses this information to shape and refine motor movement.

The nervous system is composed of nerve cells, called neurons, and support cells, called glia. Communication throughout the nervous system is achieved by electrical and chemical signaling (i.e., neurotransmitters). The primary components of a neuron are the cell body, dendrites, and synapses. Dendrites are highly branched structures that send impulses to the cell body of a neuron. The cell body is located between the dendrites and the axon, and contains the nucleus. Signals from the cell body are conducted via the axon to the axon terminal. At the terminal, neurotransmitters enter into a gap called the synapse and ultimately are transported to receptors on dendrites of neighboring neurons.

The human sensory system is our means to perceive and interpret the world around us. The conversion of sensory information from the environment, such as light, temperature, or sound, into a cellular response is sensory transduction. For example, action potentials begin by a stimulus altering the permeability of cation channels, resulting in depolarization. If the depolarization is large enough to reach threshold, an action potential fires. Action potentials are all-or-nothing responses, meaning that in most cases, they do not allow for graded responses. Information about tactile sensation is sent to the brain by these action potentials.

### 1.2.1 Somatosensory System

The somatosensory system is responsible for the perception of touch, pressure, pain, vibration, temperature, and limb orientation. These sensations begin at receptors in the skin and travel to the central nervous system. There are three subsystems that arise from the somatosensory system. The first includes touch, vibration, and pressure. The second is proprioception, and the third is temperature and pain.

Somatotopy is the correspondence of an area of the body to a specific point in the central nervous system. Using the principle of somatotopy, clinicians and scientists can employ a variety of tests to assess the functionality of the somatosensory system. Specifically, each sensor in the periphery responds to stimuli in a limited region of the body, a property called receptive fields. Receptive fields are an area of skin in which stimulation can cause a change in the firing rate of an action potential. Receptive fields vary in size across regions the body. For example, in the fingertips there are small receptive fields, but the back and legs contain much larger receptive fields. An important feature of the sensory system is that it is topographically organized, which means that neurons next to each other usually have adjacent or overlapping receptive fields. This organization is maintained from the periphery (i.e., the skin), to the spinal cord, and to sensory cortex in the post-central gyrus.

There are five classifications of somatic sensory receptors including nociceptors, thermoreceptors, proprioceptors, chemoreceptors, and mechanoreceptors. To sense touch and vibration, the skin contains mechanoreceptors. Receptive field characteristics and the density of the mechanoreceptors account for the spatial resolution in any body region that is necessary for motor movement (Vallbo & Johansson, 1984). In the hand, receptive fields are small, especially in the fingertips, with a high density of mechanoreceptors. Since tactile information is the focus of this study, mechanoreceptors are discussed in detail.

### 1.2.2 Mechanoreception

Mechanoreceptors are activated when the skin is indented, vibrated, or stretched. There are four types of mechanoreceptors in the glabrous skin of the hand (Miller, Ralston, & Kasahara, 1958):  Merkel cells, Meissiner corpuscles, Pacian corpuscles, and Ruffini endings. All four types of mechanoreceptors are activated during voluntary finger movements (Hulliger, Nordh, Thelin, & Vallbo, 1979). Mechanoreceptors are either slow- or fast- adapting. The slow-adapting receptors produce a continuous and steady response for the entire duration of stimulation. In contrast, fast-adapting receptors respond only when a stimulus begins or ends. The receptive field size of the mechanoreceptors can be large or small. Small receptive fields allow for high spatial resolution, whereas larger receptive fields have low spatial resolution (Schwartz and Krantz 2016). A high density of small receptive fields allows greater sensitivity to two-point discrimination, which is especially important for the fingertips. Two–point thresholds are best on certain parts of the body such as the fingers because of small receptive fields.

All four mechanoreceptors are encapsulated nerve endings, which are a specific type of axon that terminates within specialized skin cells. Encapsulated nerve endings allow for lower thresholds for action potential generation (Purves, 2012). A lower threshold allows these nerve endings to be more sensitive to sensory stimuli. The four mechanoreceptors must be sensitive to sensory stimuli in order to complete daily activities. Each mechanoreceptor is unique in its function.

Merkel cells are located in the epidermis of the skin and are highly sensitive to indentation. Merkel cells have a constant response to continued pressure, meaning that they are slow adapting mechanoreceptors. They have small receptive fields with densely innervated receptors, giving them high spatial resolution. They are the second most densely innervated mechanoreceptor. Merkel cells are critical for touch perception and detecting texture patterns. In particular, they are important for detecting points, edges, and curves. They have the best response to vibrations at low frequencies compared to other mechanoreceptors. Merkel cells are critical for the determination of two-point thresholds. Thus, the Merkel cells are critical for functions such as reading Braille.

Meissner corpuscles are located just beneath the epidermis, near the surface of the skin. The Meissner corpuscles filter incoming stimuli and protect nerve endings from over stimulation. Meissner corpuscles are important for detecting the beginning and ending of stimulus, meaning that they are fast-adapting mechanoreceptors. They have small receptive fields with densely packed receptors. In fact, they are the most densely innervated mechanoreceptors. Meissner corpuscles are critical for motion detection and grip control, and respond well to low frequency vibrations. They are especially sensitive to objects slipping, and are necessary for maintaining grip while playing sports. For example, in tennis, the impact of the ball on the racquet can cause slippage of the player's grip. However, instead of dropping the racquet, the Meissner corpuscles help the player detect slip and consequently increase force on the racquet.

Pacian corpuscles are located deep within the dermis of the skin and in internal organs. Their primary function is to protect sensitive nerve endings from low frequency vibration. Pacian corpuscles are also important for the detection of the beginning and ending of stimulus, meaning that they are fast-adapting mechanoreceptors. They have large receptive fields, and therefore low spatial resolution, and are the second least densely innervated mechanoreceptor. Pacian corpuscles are critical for detecting light pressure on the skin and respond well to high frequency vibration. Pacian corpuscles are necessary for fine motor control, such as writing, eating, knitting, and dressing.

Ruffini endings are located deep in the skin, as well as in ligaments and tendons (Striedter, 2016). They are sensitive to the stretch produced by finger movements. Ruffini endings have a constant response to continued pressure, meaning that they are slow-adapting mechanoreceptors. They have dispersed mechanoreceptors with large receptive fields, and therefore low spatial resolution. They are the least densely innervated mechanoreceptor. Ruffini endings are important for detecting and localizing light touch on the skin. They are necessary for tasks such as picking up a spoon to eat soup.

All four of the mechanoreceptors are present in the glabrous, or hairless, skin of the fingertips. The fingertips are the focus of this study. It is important to understand the role of different mechanoreceptors in order to evaluate somatosensation in adults with and without ADHD.  Previous studies of somatosensation report that children with ADHD have tactile processing deficits for tasks such as adaptation (processing repetitive tactile information), reaction time, static detection threshold, and simultaneous frequency discrimination (N. A. J. Puts et al., 2017). To our knowledge, such quantitative somatosensory tests have not been evaluated in adults with and without ADHD. In the next section, I detail the clinical tests of somatosensation used in this study.

## 1.3 Clinical tests of somatosensory function

### 1.3.1 Two-point Discrimination

The two-point discrimination test assesses tactile perception, and thus can help us evaluate the functioning of both the central and peripheral nervous system. In this test, two points of pressure are applied to the skin and the participant is asked to indicate when their perception changes from two to one point of pressure and vice versa. The fingertips and the face are densely innervated, meaning they have a large number of receptors in a small area, which increases sensitivity to separate pressure points. The fingertips have small receptive fields that are more numerous compared to other locations of the body. Receptive field size and density of innervation determine tactile spatial accuracy. In healthy adults, the fingertips have a two-point discrimination distance of 3-4mm (Mendoza, 2011), whereas the forearm has a discrimination distance up to 45mm (Nolan, 1982). Two-point discrimination deficits are reported for children with cerebral palsy (Tachdjian et al. 1958); however, no differences have been detected for adults with ASD (Fukuyama et al. 2017). To our knowledge, two-point discrimination for adults with ADHD has not been reported in the literature; however, since two-point discrimination can reflect how innervated the skin is, and there have been reported tactile differences in children with ADHD (Little, Dean, Tomchek, & Dunn, 2017; V. T. Shimizu, O. F. A. Bueno, & M. C. Miranda, 2014), there may be a difference in two-point discrimination thresholds in people with ADHD compared to those without.

### 1.3.2 Von Frey Filaments

The hand, most specifically the fingertips, are paramount for discriminative touch due to having a high density of mechanoreceptors (Purves, 2012). Discriminative touch can be tested with Von Frey hair monofilaments (DanMic Global, San Jose, CA) (Von Frey, 1896). Von Frey hair monofilaments are thin plastic wires that bend when pressed against a solid object. Each filament bends at a precise amount of force. Von Frey monofilaments are used to identify if the detection and discrimination of forces, is normal. Von Frey hair monofilaments are commonly used to test somatosensation on glabrous skin, such as the fingertips (McBride & Mistretta, 1982). They are endorsed by the World Health Organization for reliable measurements of somatosensation (Etter, Miller, & Ballard, 2017), and are especially useful to evaluate neuropathy (Lavery et al., 2012). In general, they are a useful clinical measure of somatosensory impairment. Von Frey hairs determine if people can detect and encode for the recognition of a force, or the recognition between two different forces.

## 1.4 The Motor System

The sensory system provides a representation of the environment and the body. A central function of the sensory system is to guide movement. All movement, whether voluntary or involuntary, requires specific patterns of muscle contractions guided by the motor system. The motor system is organized in a hierarchy, such that the upper motor neurons within the motor cortex and brain stem pass information to the local circuit neurons and lower motor neurons at the spinal cord. Information is passed to motor neuron pools, which contain lower motor neurons that directly innervate skeletal muscle, their final destination. The motor cortex and brainstem project directly to the motor neuron pools. In addition, local circuit neurons can receive sensory information from the periphery, and use this to modify activity in motor neuron pools.

Many different brain areas are involved in the control of movement. The motor cortex acts on brain stem areas and spinal motor neurons to initiate and execute a desired movement. The premotor cortex acts on the motor cortex (Cheney, 1985), and is essential for planning and directing voluntary movements. The basal ganglia are a subsystem that influence and modulate the activity of the motor cortex and the descending motor pathways. The basal ganglia suppress unwanted movements and prepare the upper motor neurons for movements (Purves, 2012). The thalamus is often referred to as the “relay station”. Similar to the basal ganglia, thalamic neurons tend to be involved in movement initiation signals (Goldberg, Farries, & Fee, 2013). Motor movement is the result of several brain structures such as the motor cortex, premotor cortex, basal ganglia and thalamus, working together.

The motor cortex is constantly coding movement parameters. For example, in reaching movements, activity in the motor cortex is related to the direction of the reach with respect to space (Fabbri, Caramazza, & Lingnau, 2010). Previous work has shown that some individual neurons in the motor cortex are solely sensitive to position, while other neurons in the motor cortex may be solely sensitive to force. The neurons that are more sensitive to force would more easily detect low force changes than large force changes (Evarts, Fromm, Kroller, & Jennings, 1983).

### 1.4.1 Grip Force

The "precision grip" is of particular importance to humans and has been the topic of a plethora of studies (Prodoehl, Corcos, & Vaillancourt, 2009 ). Precision gripping is essential for daily activities, such as dressing, writing, and holding utensils. Deficits in precision grip force output are characteristic of many disorders, including, but not limited to Parkinson's disorder (Alberts, Tresilian, & Stelmach, 1998; Vaillancourt, Slifkin, & Newell, 2001), dystonia (Nowak & Hermsdorfer, 2006), schizophrenia (Teremetz et al., 2014), and Huntington's disease (Schwarz, Fellows, Schaffrath, & Noth, 2001).

Previous work examining the neural control of grip force demonstrates that the primary motor, and premotor cortices, as well as the putamen, and cerebellum are active during both static and dynamic precision grip force control (Neely, Coombes, Planetta, & Vaillancourt, 2013). In slow and controlled force contractions, activation has been reported in the primary motor cortex, bilateral caudate nucleus, and the right dorsolateral prefrontal cortex (Spraker, Corcos, & Vaillancourt, 2009). The putamen along with the caudate nucleus are components the basal ganglia. The basal ganglia and the prefrontal cortex are effected by dopamine dysregulation, a key component of ADHD. Since these areas are important for precision grip force, they could provide insight into potential motor differences seen between adults with and without ADHD.

Recent work from our group demonstrates that in precision grip tasks individuals with ADHD produce more force than individuals without ADHD. For example, we report that when visual feedback is present, adults with ADHD produce higher force than adults without ADHD. When visual feedback was removed, a greater rate of force decrease was reported for individuals with ADHD. Further, the rate of force decrease was associated with ADHD symptomology such that increased severity of symptoms was associated with a faster rate of decay (Neely et al., 2016). In a variant of the classic Go/No Go task, adults with ADHD produced greater force on both Go and No-Go trials (Neely et al., 2017). Together, these studies suggest that individuals with ADHD may have difficulty integrating sensory feedback to adjust force output to the demands of the task, or that greater force output is a reflection of hyperactivity in the motor system. A first step to examining these alternate explanations is the investigation of force output at a variety of amplitudes, in conjunction with clinical somatosensory tests relevant to the index finger and thumb. We are particularly interested in manipulations in amplitude because the activity of subthalamic nucleus and the globus pallidus internus scale to force amplitude in healthy young adults (Spraker, Yu, Corcos, & Vaillancourt, 2007). These regions are critical in the pathology of ADHD. Thus, we replicate the paradigm reported in Spraker et al. (2007) in a sample of young adults with and without ADHD. In addition, all participants completed a battery of somatosensory tests, as well as a sensory profile during the same laboratory visit such that we can evaluate the relationship between motor and sensory tasks.

## 1.5 Current Study and Hypothesis

The goal of the current project is to determine whether deficits in somatosensory perception exist, and if so, whether they are related to grip force output and/or self-reported sensory experiences and ADHD-related symptoms in young adults with and without ADHD. Reports show that 2.6% adults with ADHD have a tactile disability described as paresthesia (Bijlenga, Tjon-Ka-Jie, Schuijers, & Kooij, 2017). However, this deficit has rarely been quantified, and never examined in concert with a precise, continuous motor task. The current study addresses this gap by evaluating clinical somatosensory measures and precision grip force output in young adults with and without ADHD. In addition, we examine the relationship of self-report of sensory experiences and ADHD-related symptoms to quantitative somatosensory tests and force output.

Previous studies report that individuals with ASD have sensory deficits (Marco, Hinkley, Hill, & Nagarajan, 2011). The majority of these studies involve pediatric, and not adult, samples. In a study completed by Clince, Connolly, and Nolan (2016) adults with ASD or ADHD report having different sensory experiences than the general population. In addition, Clince et al. found that in most sensory subscales of the Adult/Adolescent Sensory Profile (AASP) (i.e. Low Registration, Sensation Seeking, Sensory Sensitivity, Sensation Avoiding) there were no major differences between ASD and ADHD groups (Clince, Connolly, & Nolan, 2016). This demonstrates similar symptomology seen in ADHD and ASD could be explained by a similar increased sensitivity to stimuli.

Puts et al. (2013) employed a battery of vibrotactile tasks assessing cortical mechanisms and aspects of behavior. Tasks were performed by both adults and typically developing children to determine the feasibility of the tasks in both cohorts (N. A. Puts, Edden, Wodka, Mostofsky, & Tommerdahl, 2013). This battery of tasks was then used to compare tactile processing in typically developing children to children with ADHD. Puts et al. report that children with ADHD were not affected across all tactile domains. Tactile processing differences were seen in tasks with repetitive tactile information or, tactile “adaptation”. Worse performance on adaptation tasks by children with ADHD may explain hyper-responsiveness in ADHD. Puts et al. found higher detection thresholds than controls, and an inability to detect weak ongoing stimulation in children with ADHD (N. A. J. Puts et al., 2017).

The current protocol includes clinical somatosensory tests and visually guided motor tasks. The somatosensory tests include the two-point discrimination task, tactile-detection with the Von Frey hairs, and tactile-discrimination threshold estimates with the Von Frey hairs. Motor tests include a visually guided grip force task, grip strength, and a coordination task. All Participants self-report about their sensory experiences via a sensory profile questionnaire. Since we demonstrated that adults with ADHD produce more force than adults without ADHD (Neely et al., 2016), we plan to confirm these results. We test three hypotheses. First, consistent with previous work (Spraker et al., 2007), we expect to find greater variability in force output at lower amplitudes. Second, we hypothesize that somatosensory measures with the Von Frey hair monofilaments will be correlated with error in the low amplitude, but not high amplitude, force tasks, because neurons that are sensitive to force are able to detect low force changes more easily than high force changes (Evarts et al., 1983). Third, we test the hypothesis that the mean force output will be correlated with somatosensory function, suggesting that poor somatosensation may be the cause of excessive force, such as poorer somatosensory discrimination and higher somatosensory thresholds, in adults with ADHD compared to adults without ADHD.

# Chapter 2

# METHODS

## 2.1 Participants

Participants ages 18-25 were recruited from an existing database of research participants from Dr. Neely's Brain and Behavior Laboratory. Individuals in this database participated in at least one laboratory session during which research staff conducted a diagnostic interview for ADHD. Specifically, diagnosis was confirmed by using DSM-V (American Psychiatric Association, 2013) criteria as determined by the Conners' Adult ADHD Diagnostic Interview (CAADID, Multi-Health Systems Inc., for details see (Neely et al., 2017)). Exclusion criteria included a history of seizures, epilepsy, meningitis, encephalitis, or autism spectrum disorder, as well as concussion that resulted in loss of consciousness for more than 10 minutes, or previous diagnosis of a disorder involving psychosis. Individuals were invited to participate in the current study if they were right-handed and had a confirmed diagnosis of ADHD, or had never had a diagnosis of ADHD.

### 2.1.1 Adults with ADHD

The results of the CAADID diagnostic interview, conducted in advance of the current study, were used to confirm diagnosis of ADHD. Individuals with ADHD showed five or more symptoms of inattention or hyperactivity, and these symptoms had to impair everyday life in at least two settings, such as family and work. Nineteen participants met the criteria for ADHD. Adults reporting less than three total symptoms and less-than or equal-to two symptoms of inattention or hyperactivity were age and sex-matched controls for the ADHD group. A total of 19 participants met this criterion.

## 2.2 Procedures

All participants were given a brief explanation of the study and then completed a written informed consent. All procedures were approved by the Institutional Review Board at The Pennsylvania State University, and were consistent with the Declaration of Helsinki. Participants were compensated with cash at the end of the data collection session. During the lab visit, participants completed a battery of somatosensory and motor tasks (described below) in less than two hours.

## 2.3 Somatosensory Tasks

Somatosensory tasks evaluated the perception of touch on the right hand. Two-point discrimination-threshold estimates, tactile detection-threshold estimates, and tactile-discrimination-threshold testing were conducted.

### 2.3.1 Two-Point Discrimination-Threshold Testing

As shown in Figure 2.1A, this task used discrimination disks (BASELINE 2-point Discrim-A-Gon 12-1492(D2)), octagon shaped wheels containing fixed eight 2-point intervals.

The fixed two-point intervals increased by 1mm, from a single point to two points separated by a 15mm. The points were applied perpendicularly to the thumb, index finger, as shown in Figure 2.1B, and hypothenar muscle region of the palm. A method of limits approach was used (George A. Gescheider, 1997). Participants were asked to close their eyes and verbally indicate when the point of pressure switched from two points to one point and vice versa. Alternating ascending and descending order of the intervals was used. Six trials on the thumb, index finger and palm were completed. The average of the six trials was the participant's two-point discrimination threshold estimate.

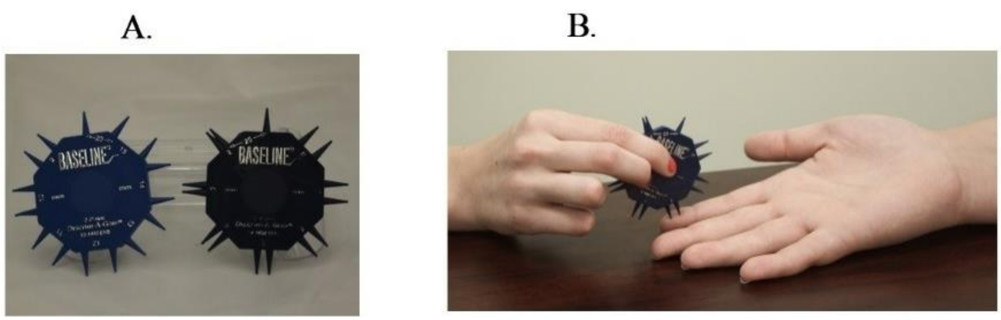


**Figure 2-1** Two-point Discrimination Disks (A) Discrimination disks. (B) Points on the disk were applied to the index finger.

### 2.3.2 Tactile Detection-Threshold Estimates

As shown in Figure 2.2A, Von Frey hair monofilaments were used to determine the minimum force detected on the thumb, index finger, and palm (DanMic Global, San Jose, CA). Von Frey hair monofilaments are thin plastic wires that produce different forces when pressed against a solid object. The forces produced ranged from 0.008g to 300g. Monofilaments were applied perpendicularly to the skin. Importantly, participants completed this task with their eyes closed. Threshold estimates were determined with a two-alternative forced-choice paradigm (G.

A. Gescheider, Bolanowski, Zwislocki, Hall, & Mascia, 1994). As shown in Figure 2.2B, participants laid their hand flat, in a supine position on a table. The experimenter said “trial one”, “trial two”, while simultaneously applying the Von Frey hair in only one of the trials. Participants were to verbally indicate the trial in which they felt the point of pressure. When participants succeeded in selecting the correct response for three sequential trials of the same force, the next Von Frey hair of smaller force was applied. If participants made an incorrect choice, then the monofilament of next higher force was applied. The task ended after a specific force was tested five times, and that force was determined to be the detection-threshold estimate. If participants succeeded in selecting the correct trial for the lowest force available (0.008 g), five times in a row, the task ended and that value was the detection-threshold estimate.

### 2.3.3 Tactile Discrimination-Threshold Estimates

To determine tactile discrimination-threshold estimates, we used the Von Frey hair monofilaments described in the previous section. This task is identical to the previous task with the exception that two different Von Frey hairs were applied separately, that is, a different Von Frey hair was applied in each of two trials. Participants verbally indicated which of the two trials contained the stronger point of pressure. Participants began discrimination trials at three monofilament force levels above their detection-threshold estimate.

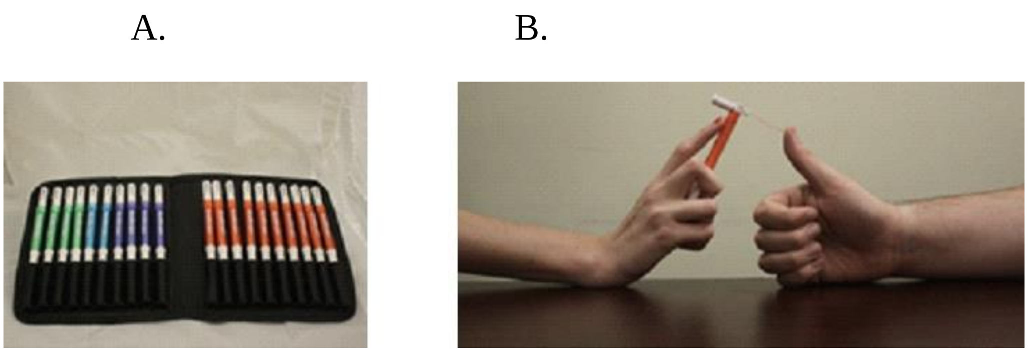


**Figure 2-2** Von Frey Hair Monofilaments. (A) Monofilaments (B) Monofilaments were applied to the thumb

### 2.3.4 AASP

Using Qualtrics, all participants completed the Adolescent/Adult Sensory Profile (AASP) (Brown & Dunn, 2002), a 60-item, self-report questionnaire about everyday sensory experiences. Participants rated statements such as “I enjoy being close to people who wear perfume or cologne”, or “I become bothered when I see lots of movement around me (for example, at a busy mall, parade, or carnival)”. Response options were: “Almost Never” (5 % of time), “Seldom” (25% of time), “Occasionally” (50% of time), “Frequently” (75% of time), and “Almost Always” (95% of time). Responses were scored by a point system: “Almost Never” =1,“Seldom” =2, “Occasionally” = 3, “Frequently” =4 and “Almost Always” =5. The questionnaire has four subscales derived from Dunn’s Model of Sensory Processing (1997): “Low Registration”, “Sensation Seeking”, “Sensory Sensitivity”, and “Sensation Avoiding”.  The points from participants’ ratings were summed to obtain the Quadrant Raw Score Total. The Quadrant Raw Score Total can then be compared to norms.

## 2.4 Motor

Motor tasks, described below, assessed dexterity, strength, and visually guided force control.

### 2.4.1 Purdue Pegboard

Participants completed the Purdue Pegboard (Buddenberg & Davis, 2000) task to measure dexterity and coordination. Participants were given 30 seconds to place as many pins as possible in a row of small holes. To this end, participants picked up a pin with their right hand from the bin furthest to their right, and then placed the pin in the right-hand column. All participants completed two trials. Participants were instructed that they if they dropped a pin, they should not retrieve it, but instead get another pin and continue with the task. The Pegboard task is scored by counting how many pins were successfully placed in the allotted time. We also recorded how many pins were dropped. An average was calculated for number of pins placed and number of pin drops for the two trials of each task.

### 2.4.2 Strength Task

Participants' maximum voluntary contraction (MVC) was calculated using a pinch grip dynamometer (Lafayette Hydraulic Pinch Gauge, Model J00111, Lafayette, IN). Participants were instructed to produce the maximum force they could by pinching on the dynamometer. The average of three 5-s pinch trials determined the participants' MVC.

### 2.4.3 Precision Grip Force Task

All participants completed a visually guided precision grip force task. Importantly, target force amplitudes were determined from each participant's MVC. Participants sat in a chair with a specially designed armrest that comfortably supports their forearm. As shown in Figure 2.3A, participants produced force with their index finger and thumb against a custom-built precision grip apparatus. Specifically, participants pressed on two opposing ELFF-B4 model load cells constructed from piezoresistive strain gauges (Measurement Specialties, Hampton, VA). The force from each load cell was collected using Coulbourn Instruments Type B V72-25B amplifiers at an excitation voltage of 5 V. The force signal was digitized at 62.5Hz by a 16-bit A/D converter (National Instruments, Austin, TX). This data was further transformed to Newtons using a calibration factor calculated by using known weights. Force levels as low as 0.0016 N could be detected. Custom-written programs in LabVIEW (National Instruments, Austin, TX) were used to conduct voltage data acquisition, voltage-to-force transformation, and stimulus presentation.

A 102cm Samsung television screen placed a distance of 127cm in front of the participants provided real-time visual feedback instructing the participants when and how hard to press. The TV had a resolution of 1920 x 1080 and a 120Hz refresh rate. As shown in Figure 2.3B, the visual display contained two bars on a black background. At the start of each run, a red/green bar and white bar were displayed. The white bar was stationary and represented the target amplitude. The red/green bar moved up and down in real-time as the participants increased and decreased force, respectively. When the bar was red, participants were to rest, whereas when the bar was green, participants were to press. Participants were instructed to move the green bar up to the white bar as quickly and accurately as possible, hold it there, covering the white bar, until the green bar turned red. During the "rest" time, participants were to keep their fingertips in contact with the load cells, but without applying force to the load cells. This ensured a consistent hand position throughout the task.

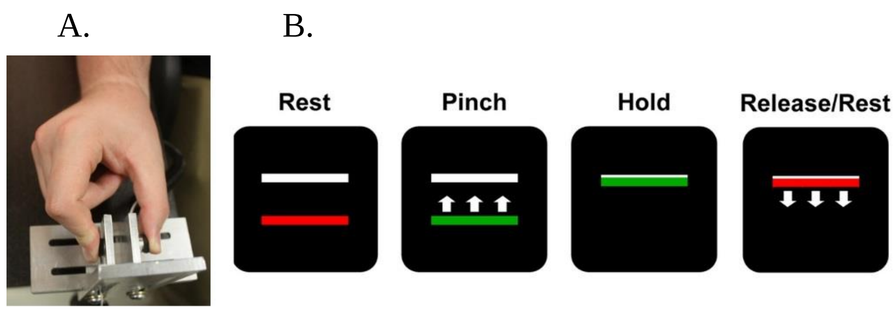


**Figure 2-3** The Precision Grip Force Task. (A) Precision grip apparatus. (B) Visual display contained two horizontal bars.

Participants completed the task at seven amplitudes: 5%, 10%, 15%, 20%, 30%, 40% and 50% of their MVC. The experimental timeline is shown in Figure 2.4. As shown in 2.4A, trials were completed in "runs", and a run consisted of four 30-s blocks of force at the same target amplitude. Thus, participants were able to predict the amount of force required for the entire run. The 30-s force production block was preceded and followed by 12-s of rest. As shown in Figure 2.4B, participants completed five trials within each 30-s block. A trial consisted 4-s force pulses separated by 2-s of rest. Therefore, for each amplitude, participants completed four runs with five trials in each run, for a total of 20 trials per amplitude. The timeline of each run was identical and the entire run was 180 s. Figure 2.4C shows the force production at different amplitudes.

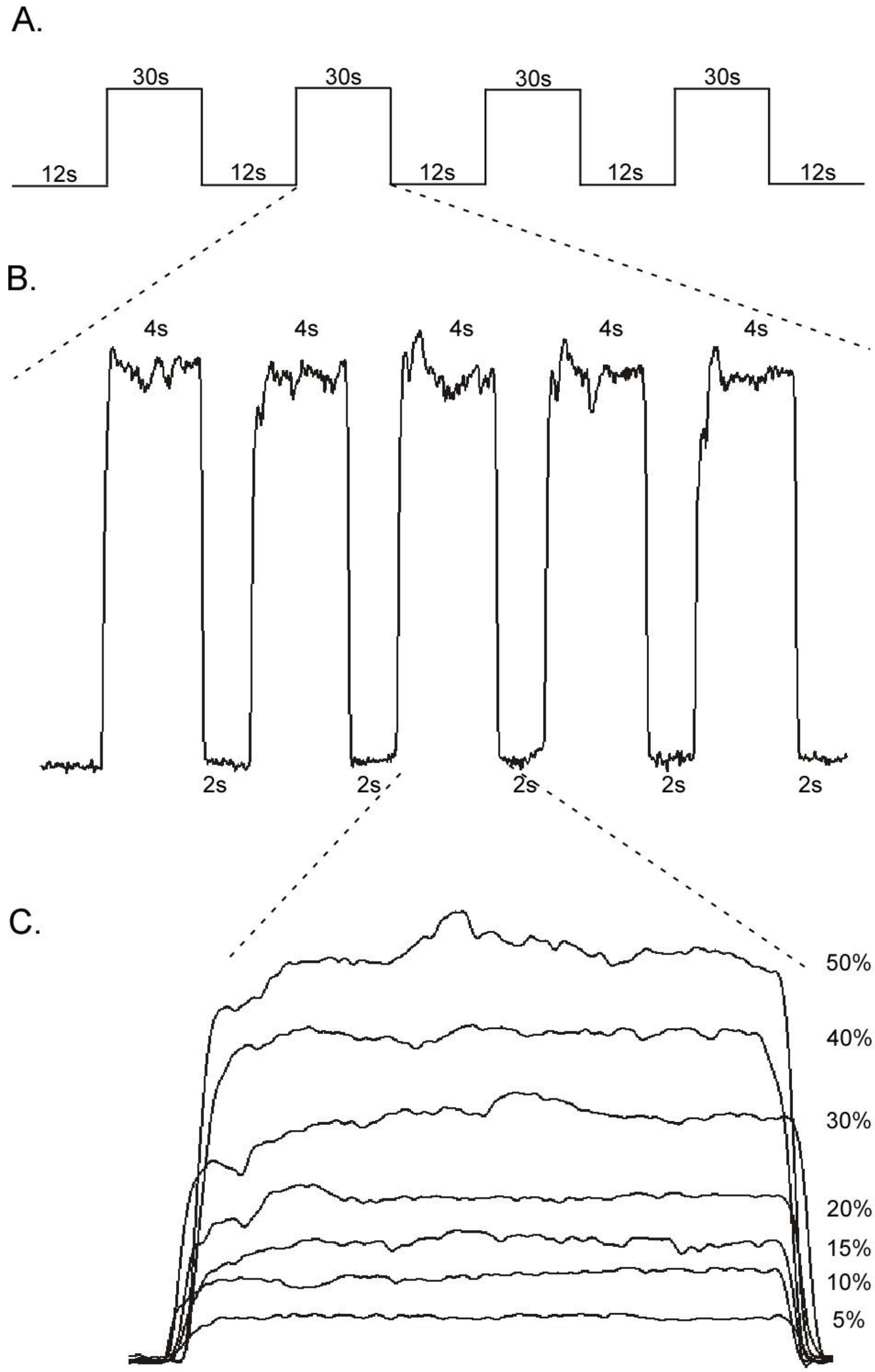


**Figure 2-4** Breakdown of the Precision Force Task (A) The timeline of events in each condition. (B) Raw force output from an exemplar subject in the 20% MVC condition. Five 4 s trials were completed within each force block, for a total of 20 trials. (C) The raw force output illustrates the 5, 10, 15, 20, 30, 40, and 50% MVC conditions in one 4 s trial.

After each session, force output was digitally filtered with a tenth-order Butterworth filter with a 15Hz low-pass cutoff frequency. MATLAB (Math Works Natick, Massachusetts) was used to determine four key time points for each trial. As shown in Figure 2.5, the four time points were onset of force, beginning and end of force production, and offset of force. The 12s rest periods as well as the 2s rest intervals in between trials were not accounted for in the analysis. Custom-written programs in MATLAB calculated the mean force, standard deviation, coefficient of variability, root mean square error, on-rate, off-rate, and duration time for each participant, in each of the seven amplitude conditions. These variables were output for each trial, and then averaged across trials to generate a mean for each participant, at each amplitude.

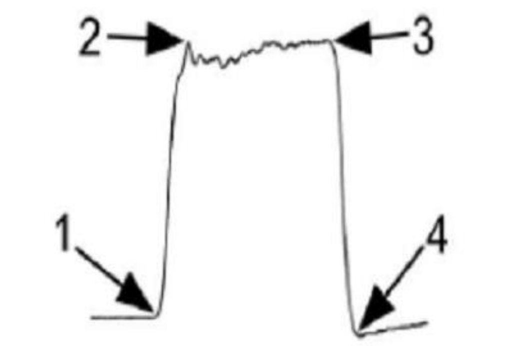


**Figure 2-5** Four key time points that were marked for each 4-s trial. (1) The first at the onset of force production, (2) the second point when they reached the target amplitude, (3) the third point at the onset of decreased force, and (4) the last point at the end of force production.

# Chapter 3

# RESULTS

## 3.1 Participants

As reported in Table 3.1, independent univariate Analysis of Variance (ANOVA) for group (ADHD, Control (CTRL)) showed no group difference for age or IQ. As measured by the CAADID interview, the ADHD group reported a more inattention, hyperactivity/impulsive, and total ADHD symptoms in adulthood compared to the control group, ps < .001. As measured by the CAARS (K. Conners et al., 1999), the ADHD group reported a larger number of inattention/memory problems, hyperactivity/restlessness symptoms, and the index T-score, which consists of the best items on the CAARS to evaluate adults “at risk” for ADHD, ps < .001.

**Table 3-1**
*Participant characteristics*

| Variables | Group | | Significant Group Differences |
|---|---|---|---|
| | Control | ADHD | |
| **Sample size** | 19 | 19 | |
| Females | 13 | 13 | |
| **MVC, Newtons** | | | |
| Right Pinch | 40.50 (8.07) | 35.43 (9.23) | |
| Right Hand | 290.06 (90.05) | 308.86 (109.04) | |
| **Age, yrs** | 21.53 (2.01) | 21.84 (1.98) | ADHD = CTRL, t(36) = -0.49, p = .629 |
| **FSIQ** | 111.79 (12.01) | 108.63 (7.21) | ADHD = CTRL, t (36) = 0.98, p = .332 |
| **CAADID** | | | |
| Number of inattention symptoms endorsed in adulthood | .2105 (.60) | 6.79 (1.81) | ADHD > CTRL, F(1, 36) 223.21 p < .001 |
| Number of hyperactive/impulsive symptoms endorsed in adulthood | .0000 (.00) | 5.05 (2.39) | ADHD > CTRL, F(1, 36) = 242.53 p < .001 |
| Total number of symptoms endorsed in adulthood | .2105 (.63) | 11.84 (3.02) | ADHD > CTRL, F(1, 36) = 269.51 p < .001 |
| **CAARS-S:L** | | | |
| ADHD Index | 39.21 (6.06) | 62.05 (9.52) | ADHD > CTRL, F(1, 36) = 77.85, p < .001 |
| Hyperactivity/restlessness | 41.79 (6.00) | 59.00 (9.53) | ADHD > CTRL, F(1, 36) = 44.41, p < .001 |
| Inattention/Memory | 38.26 (5.46) | 64.42 (12.47) | ADHD > CTRL, F(1, 36) = 70.18, p < .001 |
| **AASP** | | | |
| Raw Item Score Low Registration | 27.31 (5.13) | 43.74 (9.58) | ADHD > CTRL, F(1, 36) = 43.34, p < .001 |
| Raw Item Score Sensation Seeking | 47.11 (8.94) | 49.79 (5.81) | ADHD = CTRL, F(1, 36) = 1.203, p = .280 |
| Raw Item Score Sensory Sensitivity | 31.26 (7.64) | 44.63 (7.48) | ADHD > CTRL, F(1, 36) = 26.67, p < .001 |
| Raw Item Score Sensation Avoiding | 34.42 (6.57) | 41.26 (5.95) | ADHD > CTRL, F(1, 36) = 11.32, p < .05 |

## 3.2 Somatosensory

To examine group differences in somatosensory tests, we first conducted a Multivariate Analysis of Variance (MANOVA) for group (ADHD, CTRL) for each dependent variable: two-point discrimination, tactile detection-threshold estimates, and tactile discrimination-threshold estimates for the right index finger, right thumb, and right palm. The results of this analysis did not reveal group differences, $F(9, 28) = 0.74$, $p = .667$. Therefore, additional analyses for each subgroup of tests (i.e., discrimination disks, tactile detection-threshold estimates and tactile-discrimination estimates) were not conducted. The group means and standard deviations for each test are shown in Figure 3.1.

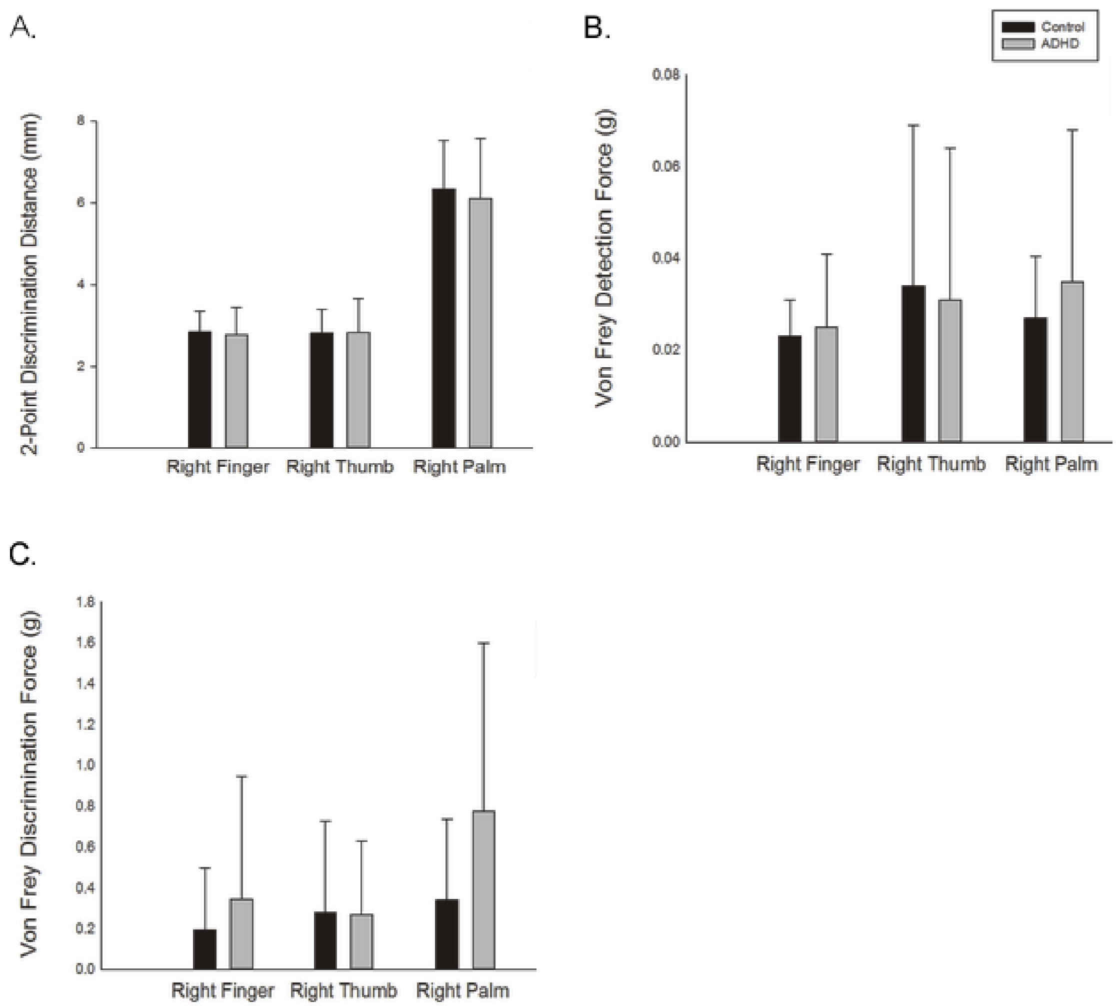


**Figure 3-1** Average Somatosensory Task Scores for Participants with and without ADHD .The means and standard deviation for the (A) two-point discrimination-threshold estimate task, (B) tactile detection-threshold task, and (C) tactile discrimination-threshold estimate task, on the index finger, thumb, and palm in participants with and without ADHD.

**3.3 Adolescent/ Adult Sensory Profile**

To examine group differences on the AASP, we evaluated Raw Item Scores, which were a summation of the ratings for the 15 questions in each of the four different subscales. First, we conducted a MANOVA for group (ADHD, CTRL) for each subscale: Low Registration, Sensation Avoiding, Sensation Seeking, and Sensory Sensitivity. The results of this analysis demonstrated a multivariate effect of group, $F(4, 33) = 10.27$ , $p < 0.001$. Therefore, additional analyses for each subscale were conducted via separate univariate ANOVAs. As shown in Figure 3.2, group differences were revealed for Low Registration, Sensation Avoiding, and Sensory Sensitivity, Fs $(1,36) = 43.34, 11.32, 26.67$, respectively, ps $< .002$. However, no differences were observed for Sensation Seeking, $F(1,36) = 1.203$, $p = .280$.

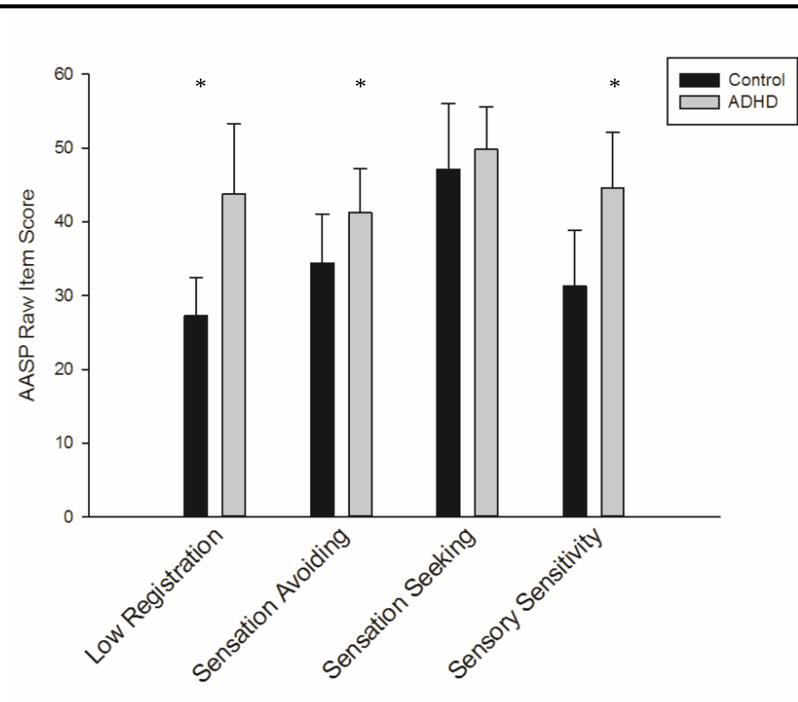


**Figure 3-2** Average AASP Raw Item Scores for Participants with and without ADHD. The means and standard deviation for the raw item score of the four subgroups of the Adult Adolescent Sensory Profile for adults with and without ADHD. The asterisk symbol indicates a significant difference between groups.

**3.4 Motor Tasks**

To examine group differences in force output, we first conducted a MANOVA for group (ADHD, CTRL) for each dependent variable: mean, standard deviation, coefficient of variability, root mean square error, on-rate, off-rate, and duration time or average time spent producing force. For each dependent variable, the MANOVA revealed an effect of amplitude, all Fs(6, 31) > 16.994, ps < .001. However, we did not observe an interaction between amplitude and group, all Fs(6, 31) < 1.83, ps > .125. We then evaluated the effect of amplitude via repeated measures ANOVA for each dependent variable. When Sphericity was violated, the Greenhouse Geiser analysis was used. As anticipated, an effect of amplitude was revealed for all dependent variables, Fs(6, 216) > 20.86, ps < .001 .We did not observe a main effect for group for any dependent variables, Fs (1, 36) < 2.987, ps > .092. Likewise, we did not observe a group by amplitude interaction for any dependent variables Fs (6, 216) < 1.817, ps > .166. Tables 3.2-3.8 report the full statistics for each dependent variable. Means and standard deviations are shown in Figure 3.3.

**Table 3-2**

*Statistical Tests for the Mean Force Produced during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 34643.42 | < .001 |
| Amplitude x Group | 6, 31 | 1.08 | .396 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 704.08 | < .001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 1.02, 36.83 | 1301.86 | < .001 |
| Amplitude x Group | 1.02, 36.83 | 1.81 | .285 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 0.19 | .666 |

**Table 3-3**

*Statistical Tests for the Standard Deviation during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 73.221 | < .001 |
| Amplitude x Group | 6, 31 | 0.462 | .831 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 77.31 | < .001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 3.42, 122.94 | 185.39 | < .001 |
| Amplitude x Group | 3.42, 122.94 | 0.336 | .824 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 0.102 | .751 |

**Table 3-4**
*Statistical Tests for the Coefficient of Variability during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 24.41 | <.001 |
| Amplitude x Group | 6, 31 | 0.315 | .924 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 140.98 | <.001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 2.12, 76.17 | 36.43 | < .001 |
| Amplitude x Group | 2.12, 76.17 | 0.45 | .652 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 0.01 | .918 |

**Table 3-5**
*Statistical Tests for the Root Mean Square Error during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 38.67 | < .001 |
| Amplitude x Group | 6, 31 | 0.563 | .756 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 64.63 | < .001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 3.56, 128.18 | 108.75 | < .001 |
| Amplitude x Group | 3.56, 128.18 | 1.04 | .387 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| *Group* | 1, 36 | 0.167 | .685 |

**Table 3-6**
*Statistical Tests for the On-Rate during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 43.79 | < .001 |
| Amplitude x Group | 6, 31 | 1.55 | .195 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 184.11 | < .001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 2.18, 78.50 | 120.58 | < .001 |
| Amplitude x Group | 2.18, 78.50 | 1.82 | .166 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 2.99 | .092 |

**Table 3-7**
*Statistical Tests for the Off-Rate during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 46.62 | < .001 |
| Amplitude x Group | 6, 31 | 1.22 | .324 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 266.06 | < .001 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 1.50, 53.99 | 151.82 | < .001 |
| Amplitude x Group | 1.50, 53.99 | 0.302 | .677 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 0.086 | .771 |

**Table 3-8**

*Statistical Tests for the Duration Time during the Motor Task*

**Multivariate Tests**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6,31 | 16.99 | < .001 |
| Amplitude x Group | 6, 31 | 1.28 | .293 |

**Mauchly's**

| | df | Approx. Chi-Square | p |
|---|---|---|---|
| Amplitude | 20 | 29.65 | .077 |

**Tests of Within-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Amplitude | 6, 216 | 20.86 | < .001 |
| Amplitude x Group | 6, 216 | 1.49 | .184 |

**Test of Between-Subjects Effects**

| | df | F | p |
|---|---|---|---|
| Group | 1, 36 | 1.18 | .284 |

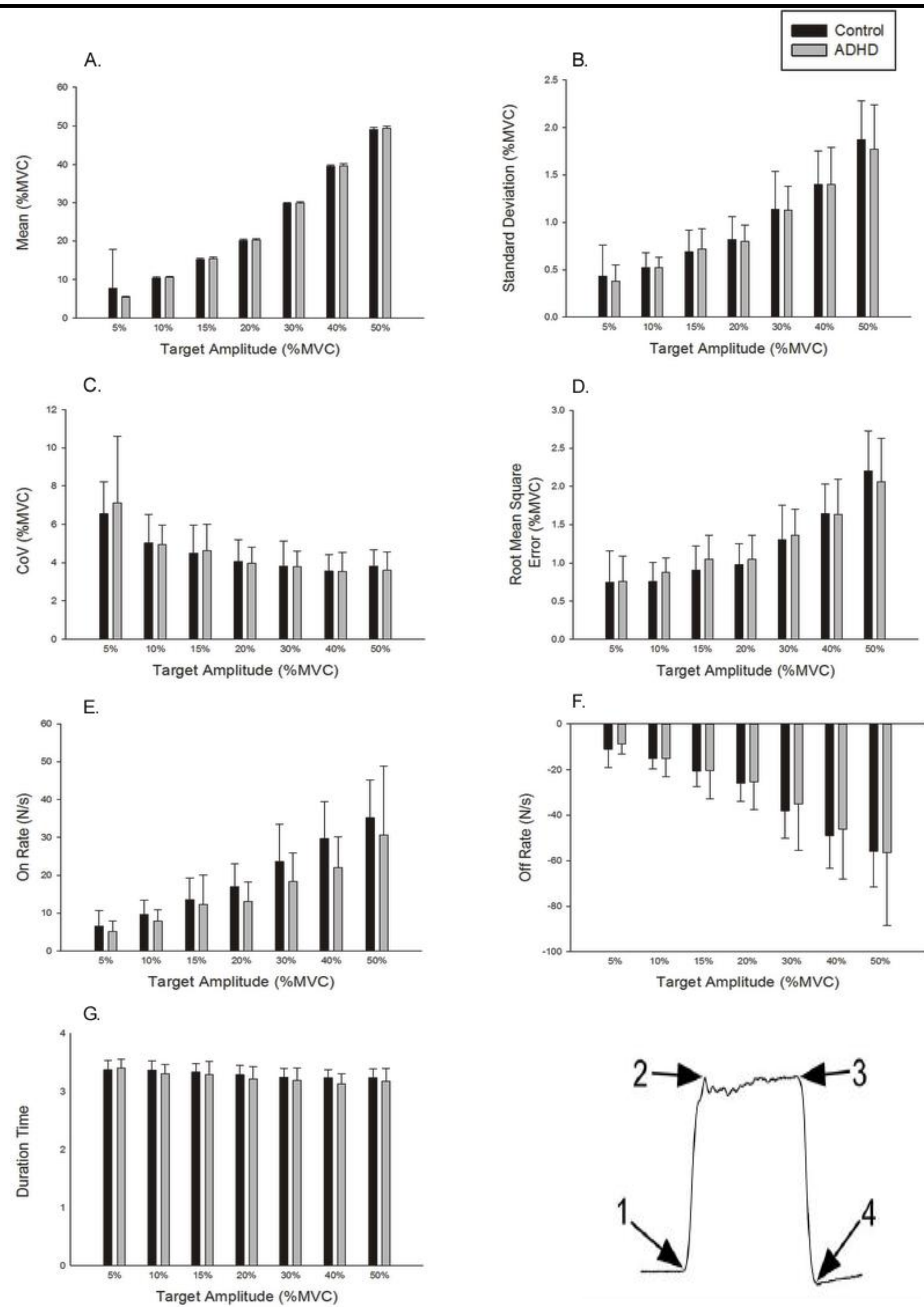


**Figure 3-3** Average Motor Tasks Measures for Each Amplitude. (A) Mean force as a function of task: the average force output between time points 2 and 3. (B) Standard deviation as a function of task: the variability of force output between time points 2 and 3. (C) Coefficient of variability (CoV), i.e., relative variability, as a function of task: the standard deviation divided by the mean. (D) Root Mean Square Error (RMSE) as a function of task: measure of the difference between actual and target force amplitudes. (E) On-Rate, i.e., rate of force increase, as a function of task: the slope of the line between time points 1 and 2. (F) Off-Rate, i.e., rate of force decrease, as a function of task: the slope of the line between time points 3 and 4. (G) Duration time as a function of task: the average time between points 2 and 3.

### 3.4.1 Purdue Pegboard

To examine group differences in the Pegboard task, we conducted a univariate ANOVA for group (ADHD, CTRL) for the number of pins placed and dropped. The results demonstrated that the control group (16.71, SD 1.51) placed more pins than the ADHD group (15.74, SD 1.40), $F(1,36)$, = 4.247, $p = .047$. However, there was no difference in the number of pins dropped $F(1,36)$, = 0.026, $p = .656$.

## 3.5 Related measures

We conducted bivariate Pearson Correlations to test the relationship between sensory tests, force output, and self-reported ADHD symptoms. Since this is an exploratory analysis, we did not correct for multiple comparisons. Comparisons of interest include: all sensory tasks with ADHD-related symptoms, motor variables with ADHD-related symptoms, motor variables with the AASP and quantitative sensory tests Tables 3.9 – 3.18 contain the correlation matrices. The matrices report the exact R values and are color-coded such that blue indicates a negative correlation and red indicates a positive correlation. In Table 3.9, the heat map overlay shows a pattern of Sensation Avoiding, Sensory Sensitivity, and Low Registration positively correlating with ADHD symptomology. In Table 3.10, the only correlation found between CoV and ADHD symptomology was in the 50% MVC condition, such that CoV 50% MVC and inattention and memory problems were negatively correlated. In Table 3.11, there was a consistent negative correlation between on-rate and ADHD symptomology. Table 3.12 shows no correlation observed between off-rate and ADHD symptomology. In Table 3.13, there was a positive correlation, only for the 20% MVC condition, between root mean square error and the hyperactivity/ restlessness score on the CAARS. In Table 3.14, CoV in the 10, 30, and 50 % MVC conditions was correlated with tactile discrimination-threshold estimates on the right thumb. As seen in Table 3.15, Low Registration was negatively correlated with on-rate in the 5, 20, and 40% MVC conditions. On-rate in the 10,15, and 50% MVC conditions was correlated with tactile detection-threshold estimates of the right finger and on-rate in the 15 and 50% amplitude conditions was correlated with tactile detection-threshold estimates of the right thumb. According to Table 3.16, off-rate was negatively correlated with discrimination disks, tactile detection threshold estimates for the right thumb and right finger, and tactile discrimination threshold estimates with the right finger and right palm. In Table 3.18, there were no consistent correlations of root mean square error with all sensory measures. Similarly, in Table 3.19, no consistent correlations between quantitative sensory measures and qualitative sensory measures were observed.

**Table 3-9**

*Correlations for All Sensory Measures with ADHD Symptoms*

| | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration | CAARS.ADHD.index.T.score | CAARS.Hyperactivity.Restlessness.Indext.T.score | CAARS.Inattention.memory.problems.index.T.score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DD_RTh | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 | 0 | 0.08 | -0.06 |
| DD_RF | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 | -0.2 | -0.11 | -0.18 |
| DD_RP | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 | -0.1 | -0.05 | -0.15 |
| Detection_RTh | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 | -0.11 | -0.18 | -0.04 |
| Detection_RF | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 | -0.02 | -0.1 | 0.12 |
| Detection_RP | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 | -0.1 | -0.13 | -0.01 |
| Discrim_RTh | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 | -0.1 | -0.15 | -0.04 |
| Discrim_RF | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 | 0.06 | 0.03 | 0.14 |
| Discrim_RP | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 | 0.13 | 0.23 | 0.12 |
| Sensation.Seeking | | | | | | | | | | -0.11 | 0.04 | 0.18 | 0.03 | 0.26 | 0.11 |
| Sensation.Avoiding | | | | | | | | | | | 0.74 | 0.5 | 0.45 | 0.23 | 0.47 |
| Sensory.Sensitivity | | | | | | | | | | | | 0.78 | 0.64 | 0.45 | 0.66 |
| Low.Registration | | | | | | | | | | | | | 0.8 | 0.65 | 0.83 |
| CAARS.ADHD.index.T.score | | | | | | | | | | | | | | 0.82 | 0.9 |
| CAARS.Hyperactivity.Restlessness.Indext.T.score | | | | | | | | | | | | | | | 0.69 |

**Table 3-10**

*Correlations of Coefficient of Variability of Force with ADHD Symptoms*

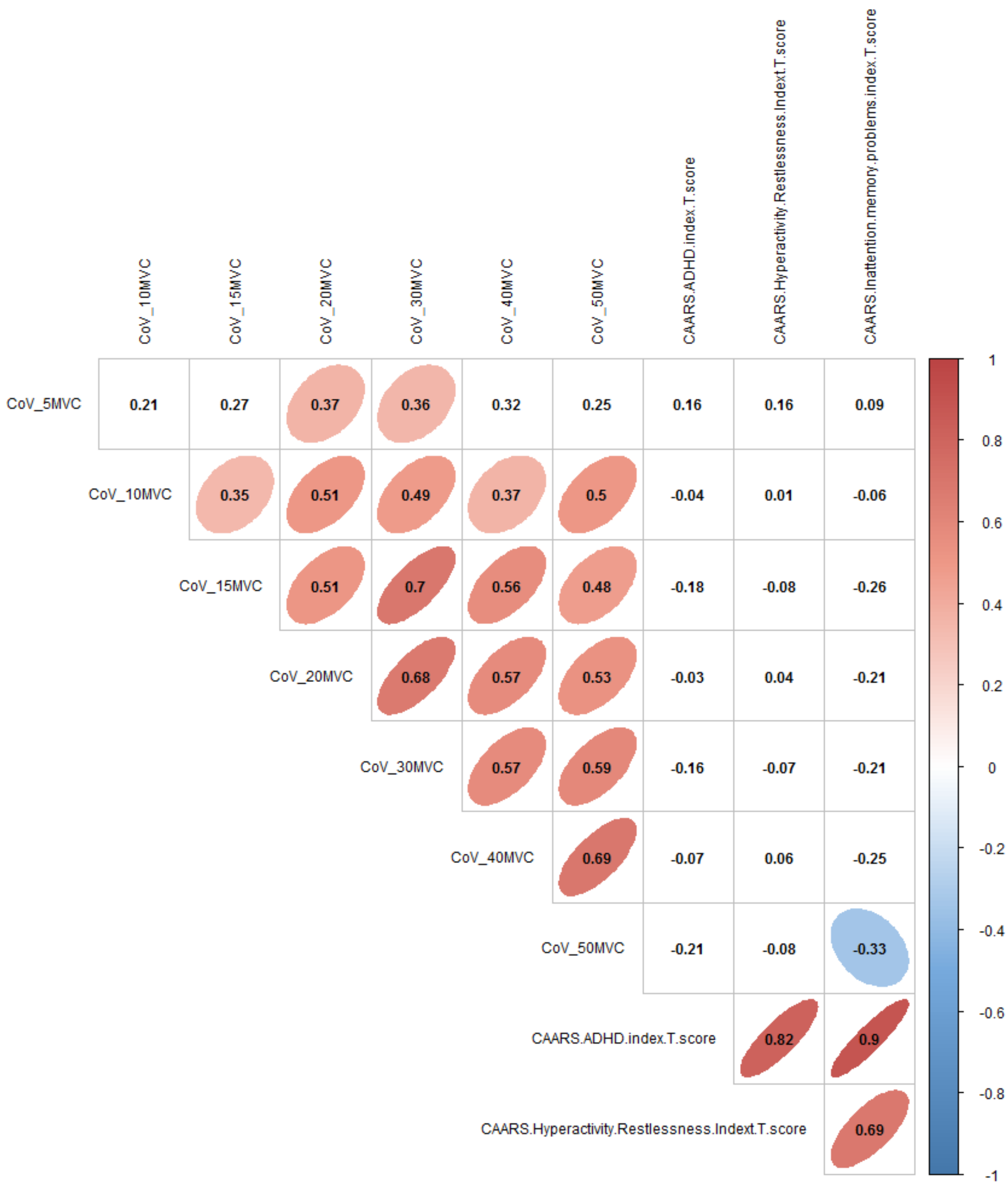

**Table 3-11**

*Correlations of On-Rate of Force with ADHD Symptoms*

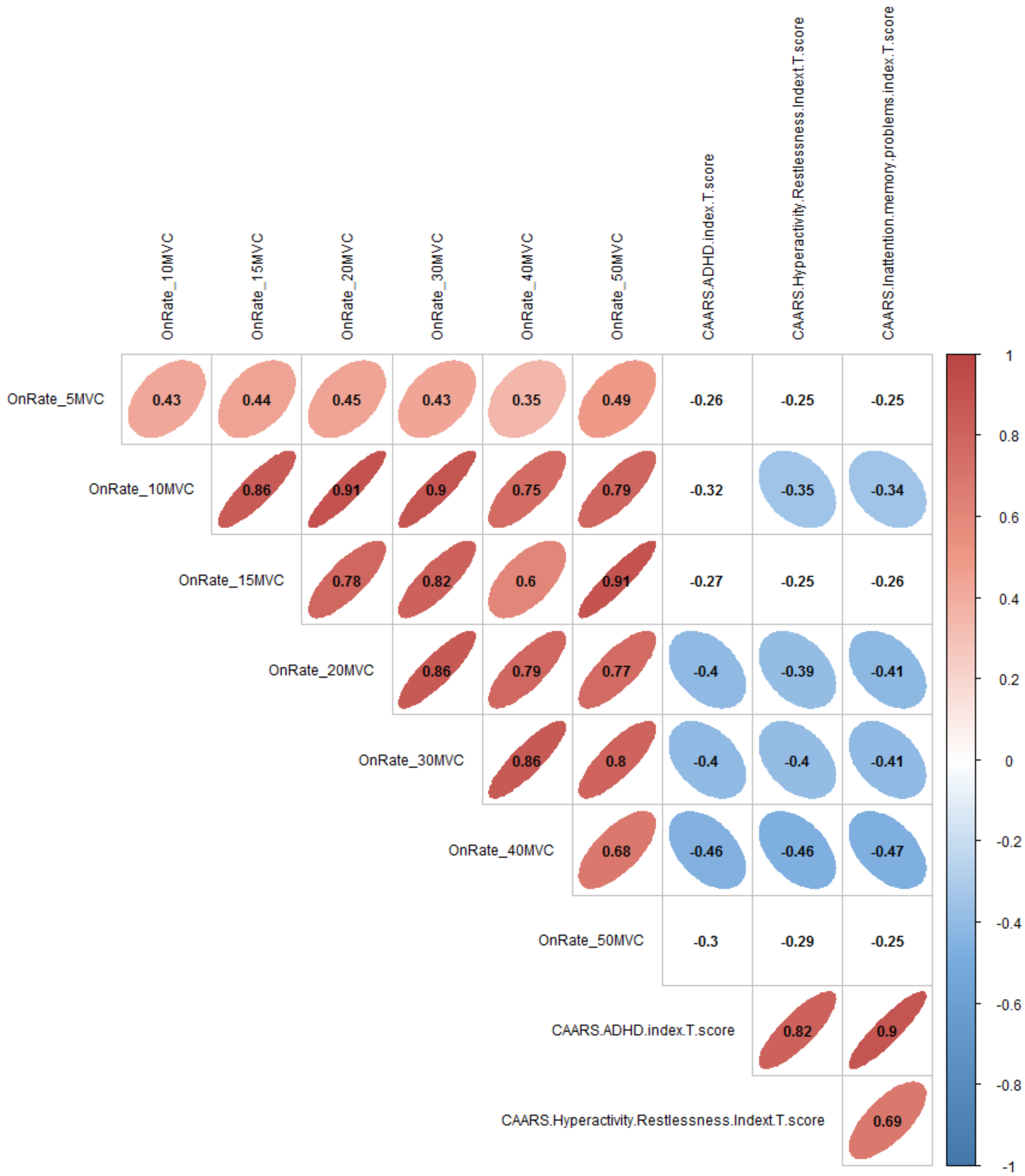

**Table 3-12**

*Correlations of Off-Rate of Force with ADHD Symptoms*

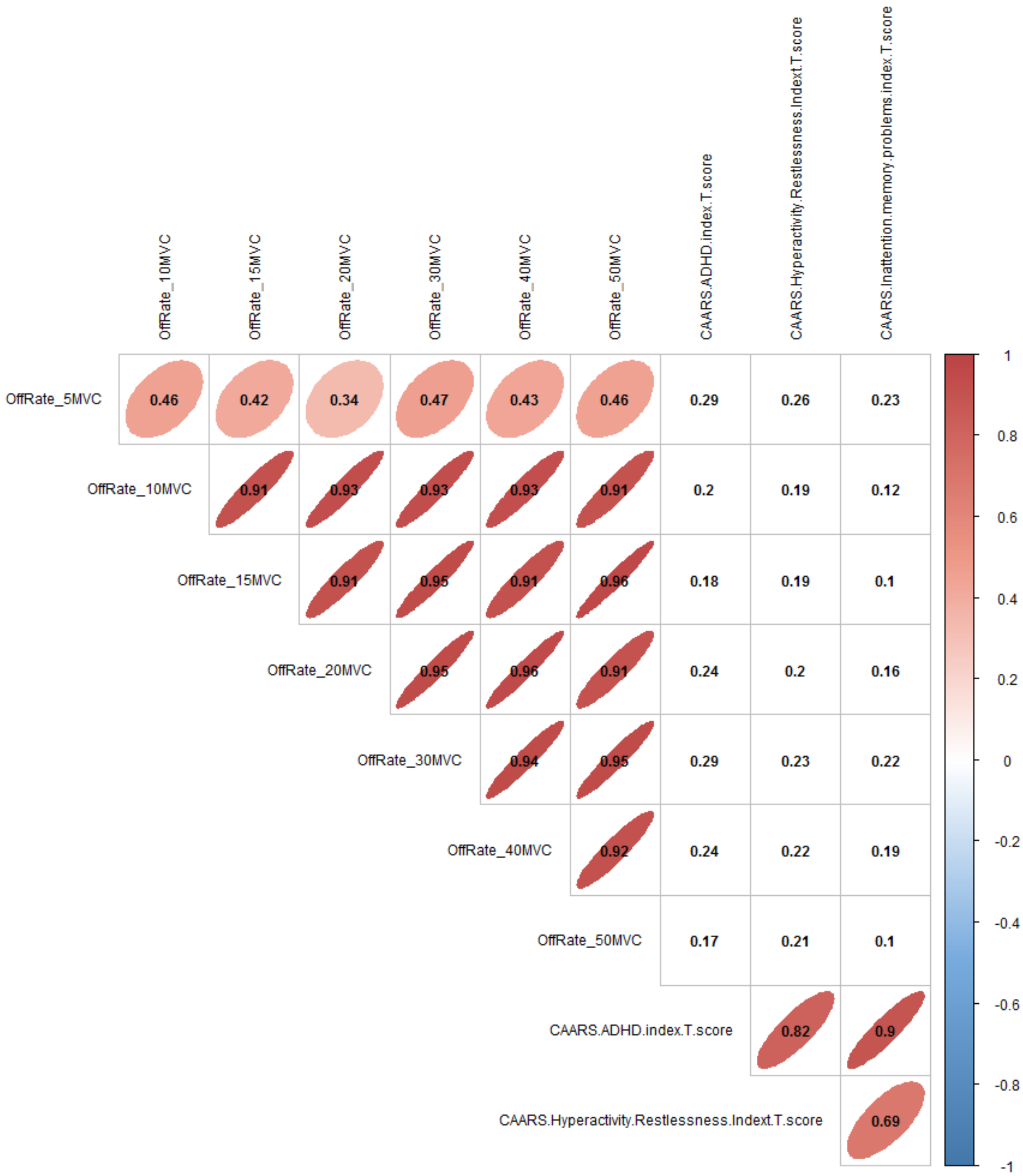

**Table 3-13**

*Correlations of Root Mean Square Error of Force with ADHD Symptoms*

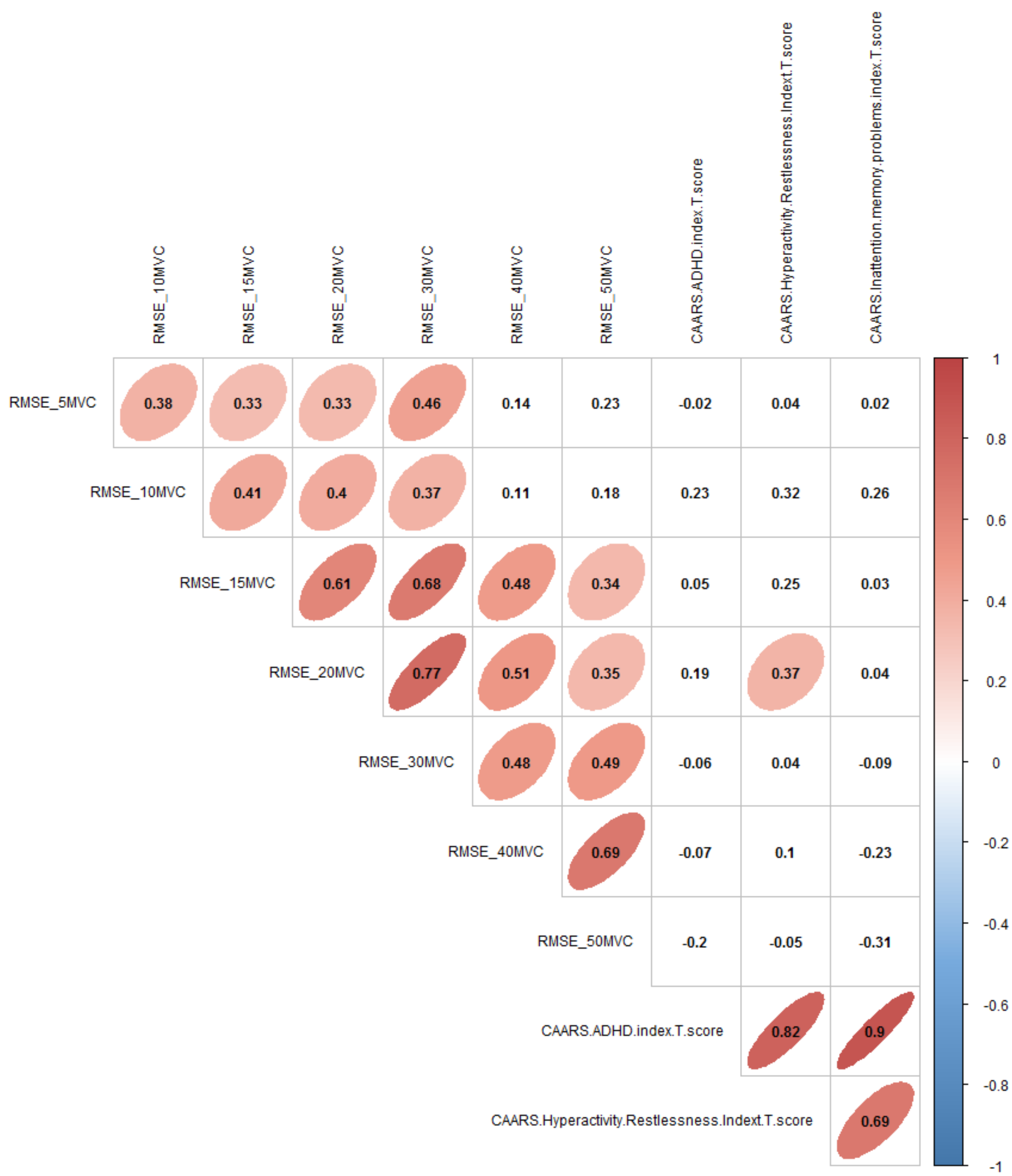

**Table 3-14**

*Correlations of Coefficient of Variability with All Sensory Measures*

| | CoV_10MVC | CoV_15MVC | CoV_20MVC | CoV_30MVC | CoV_40MVC | CoV_50MVC | DD_RTh | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CoV_5MVC | 0.21 | 0.27 | 0.37 | 0.36 | 0.32 | 0.25 | -0.07 | -0.02 | -0.05 | 0.11 | 0.03 | -0.01 | 0.1 | -0.12 | -0.06 | -0.12 | 0.06 | 0.14 | 0.15 |
| CoV_10MVC | | 0.35 | 0.51 | 0.49 | 0.37 | 0.5 | -0.21 | -0.06 | -0.08 | 0.3 | 0.08 | 0.05 | 0.36 | -0.04 | -0.12 | 0.06 | -0.03 | 0.06 | -0.04 |
| CoV_15MVC | | | 0.51 | 0.7 | 0.56 | 0.48 | 0.08 | 0.08 | -0.06 | 0.13 | 0.02 | 0.32 | 0.19 | -0.07 | 0.18 | 0.17 | -0.06 | 0.1 | -0.01 |
| CoV_20MVC | | | | 0.68 | 0.57 | 0.53 | 0.11 | 0.13 | -0.07 | 0.05 | -0.07 | -0.01 | 0.19 | -0.07 | -0.09 | 0.13 | -0.04 | 0.06 | -0.04 |
| CoV_30MVC | | | | | 0.57 | 0.59 | 0.14 | -0.05 | -0.18 | 0.23 | 0.28 | 0.2 | 0.33 | -0.02 | 0.1 | 0.19 | 0.02 | 0.07 | -0.05 |
| CoV_40MVC | | | | | | 0.69 | 0.23 | 0.34 | 0.08 | 0.14 | -0.03 | 0.34 | 0.28 | -0.04 | 0.39 | 0.08 | 0.01 | 0.11 | -0.09 |
| CoV_50MVC | | | | | | | 0.14 | 0.12 | 0.17 | 0.38 | 0.17 | 0.3 | 0.46 | -0.08 | 0.2 | 0.1 | -0.14 | -0.06 | -0.23 |
| DD_RTh | | | | | | | | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 |
| DD_RF | | | | | | | | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 |
| DD_RP | | | | | | | | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 |
| Detection_RTh | | | | | | | | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 |
| Detection_RF | | | | | | | | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 |
| Detection_RP | | | | | | | | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 |
| Discrim_RTh | | | | | | | | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 |
| Discrim_RF | | | | | | | | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 |
| Discrim_RP | | | | | | | | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 |
| Sensation.Seeking | | | | | | | | | | | | | | | | | -0.11 | 0.04 | 0.18 |
| Sensation.Avoiding | | | | | | | | | | | | | | | | | | 0.74 | 0.5 |
| Sensory.Sensitivity | | | | | | | | | | | | | | | | | | | 0.78 |

**Table 3-15**

*Correlations of On-Rate of Force with All Sensory Measures*

| | OnRate_10MVC | OnRate_15MVC | OnRate_20MVC | OnRate_30MVC | OnRate_40MVC | OnRate_50MVC | DD_RTh | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OnRate_5MVC | 0.43 | 0.44 | 0.45 | 0.43 | 0.35 | 0.49 | 0.18 | 0.37 | 0.16 | 0.22 | 0.25 | -0.02 | 0.19 | 0.04 | 0.15 | 0.15 | -0.18 | -0.35 | -0.38 |
| OnRate_10MVC | | 0.86 | 0.91 | 0.9 | 0.75 | 0.79 | 0.13 | 0.14 | 0.05 | 0.27 | 0.33 | 0.06 | 0.28 | 0.14 | 0.19 | -0.27 | 0.12 | -0.1 | -0.28 |
| OnRate_15MVC | | | 0.78 | 0.82 | 0.6 | 0.91 | 0.1 | 0.05 | 0.22 | 0.48 | 0.47 | 0.08 | 0.42 | 0.15 | 0.38 | -0.1 | 0.12 | -0.02 | -0.18 |
| OnRate_20MVC | | | | 0.86 | 0.79 | 0.77 | 0.19 | 0.2 | 0.1 | 0.27 | 0.27 | -0.02 | 0.28 | 0.1 | 0.19 | -0.26 | 0.06 | -0.17 | -0.37 |
| OnRate_30MVC | | | | | 0.86 | 0.8 | 0.2 | 0.25 | 0.13 | 0.22 | 0.31 | 0.05 | 0.23 | 0.17 | 0.27 | -0.24 | 0.07 | -0.11 | -0.29 |
| OnRate_40MVC | | | | | | 0.68 | 0.15 | 0.39 | 0.19 | 0.21 | 0.2 | 0.15 | 0.19 | 0.15 | 0.23 | -0.27 | 0.01 | -0.15 | -0.37 |
| OnRate_50MVC | | | | | | | -0.01 | 0.09 | 0.22 | 0.54 | 0.58 | 0.08 | 0.47 | 0.26 | 0.36 | -0.08 | 0.07 | -0.1 | -0.27 |
| DD_RTh | | | | | | | | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 |
| DD_RF | | | | | | | | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 |
| DD_RP | | | | | | | | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 |
| Detection_RTh | | | | | | | | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 |
| Detection_RF | | | | | | | | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 |
| Detection_RP | | | | | | | | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 |
| Discrim_RTh | | | | | | | | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 |
| Discrim_RF | | | | | | | | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 |
| Discrim_RP | | | | | | | | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 |
| Sensation.Seeking | | | | | | | | | | | | | | | | | -0.11 | 0.04 | 0.18 |
| Sensation.Avoiding | | | | | | | | | | | | | | | | | | 0.74 | 0.5 |
| Sensory.Sensitivity | | | | | | | | | | | | | | | | | | | 0.78 |

Color scale: 1, 0.8, 0.6, 0.4, 0.2, 0, -0.2, -0.4, -0.6, -0.8, -1

**Table 3-16**

*Correlations of Off-Rate of Force with All Sensory Measures*

| | OffRate_10MVC | OffRate_15MVC | OffRate_20MVC | OffRate_30MVC | OffRate_40MVC | OffRate_50MVC | DD_RTh | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OffRate_5MVC | 0.46 | 0.42 | 0.34 | 0.47 | 0.43 | 0.46 | -0.19 | -0.39 | -0.23 | -0.13 | -0.28 | 0.01 | -0.04 | -0.24 | -0.08 | -0.39 | 0.2 | 0.33 | 0.34 |
| OffRate_10MVC | | 0.91 | 0.93 | 0.93 | 0.93 | 0.91 | -0.08 | -0.25 | -0.25 | -0.35 | -0.56 | -0.14 | -0.31 | -0.49 | -0.42 | -0.07 | -0.05 | 0.05 | 0.16 |
| OffRate_15MVC | | | 0.91 | 0.95 | 0.91 | 0.96 | -0.16 | -0.24 | -0.28 | -0.39 | -0.54 | -0.12 | -0.32 | -0.52 | -0.34 | -0.01 | -0.11 | 0.02 | 0.1 |
| OffRate_20MVC | | | | 0.95 | 0.96 | 0.91 | -0.19 | -0.36 | -0.26 | -0.25 | -0.5 | -0.18 | -0.25 | -0.56 | -0.4 | -0.05 | -0.07 | 0.05 | 0.18 |
| OffRate_30MVC | | | | | 0.94 | 0.95 | -0.23 | -0.34 | -0.23 | -0.32 | -0.56 | -0.12 | -0.26 | -0.52 | -0.38 | -0.1 | -0.04 | 0.09 | 0.21 |
| OffRate_40MVC | | | | | | 0.92 | -0.13 | -0.36 | -0.32 | -0.33 | -0.49 | -0.16 | -0.29 | -0.52 | -0.4 | -0.08 | -0.07 | 0.08 | 0.19 |
| OffRate_50MVC | | | | | | | -0.14 | -0.28 | -0.3 | -0.37 | -0.58 | -0.14 | -0.27 | -0.52 | -0.38 | -0.06 | -0.12 | 0.02 | 0.1 |
| DD_RTh | | | | | | | | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 |
| DD_RF | | | | | | | | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 |
| DD_RP | | | | | | | | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 |
| Detection_RTh | | | | | | | | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 |
| Detection_RF | | | | | | | | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 |
| Detection_RP | | | | | | | | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 |
| Discrim_RTh | | | | | | | | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 |
| Discrim_RF | | | | | | | | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 |
| Discrim_RP | | | | | | | | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 |
| Sensation.Seeking | | | | | | | | | | | | | | | | | -0.11 | 0.04 | 0.18 |
| Sensation.Avoiding | | | | | | | | | | | | | | | | | | 0.74 | 0.5 |
| Sensory.Sensitivity | | | | | | | | | | | | | | | | | | | 0.78 |

**Table 3-17**

*Correlations of Root Mean Square Error of Force with All Sensory Measures*

| | RMSE_10MVC | RMSE_15MVC | RMSE_20MVC | RMSE_30MVC | RMSE_40MVC | RMSE_50MVC | DD_RTh | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RMSE_5MVC | 0.38 | 0.33 | 0.33 | 0.46 | 0.14 | 0.23 | 0.13 | 0.15 | -0.09 | -0.05 | 0.03 | -0.08 | -0.06 | -0.12 | -0.2 | 0.24 | -0.04 | -0.05 | 0 |
| RMSE_10MVC | | 0.41 | 0.4 | 0.37 | 0.11 | 0.18 | -0.08 | -0.19 | -0.23 | -0.01 | -0.1 | 0.06 | 0.15 | -0.14 | -0.04 | 0.1 | 0.11 | 0.13 | 0.13 |
| RMSE_15MVC | | | 0.61 | 0.68 | 0.48 | 0.34 | 0.16 | -0.01 | -0.1 | 0.12 | 0.12 | 0.17 | 0.29 | -0.11 | 0.38 | 0.21 | 0.03 | 0.16 | 0.07 |
| RMSE_20MVC | | | | 0.77 | 0.51 | 0.35 | 0.17 | -0.05 | -0.15 | -0.01 | -0.1 | -0.13 | 0.15 | -0.14 | -0.09 | 0.11 | 0.14 | 0.12 | 0.1 |
| RMSE_30MVC | | | | | 0.48 | 0.49 | 0.15 | -0.08 | -0.2 | 0.17 | 0.17 | 0.13 | 0.28 | -0.07 | -0.01 | 0.11 | 0.12 | 0.11 | 0 |
| RMSE_40MVC | | | | | | 0.69 | 0.23 | 0.29 | -0.08 | 0.1 | -0.08 | 0.28 | 0.28 | -0.05 | 0.35 | 0.05 | -0.04 | 0.05 | -0.18 |
| RMSE_50MVC | | | | | | | 0.15 | 0.09 | 0.13 | 0.16 | -0.01 | 0.22 | 0.3 | -0.12 | 0.17 | 0.04 | -0.19 | -0.1 | -0.21 |
| DD_RTh | | | | | | | | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 |
| DD_RF | | | | | | | | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 |
| DD_RP | | | | | | | | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 |
| Detection_RTh | | | | | | | | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 |
| Detection_RF | | | | | | | | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 |
| Detection_RP | | | | | | | | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 |
| Discrim_RTh | | | | | | | | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 |
| Discrim_RF | | | | | | | | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 |
| Discrim_RP | | | | | | | | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 |
| Sensation.Seeking | | | | | | | | | | | | | | | | | -0.11 | 0.04 | 0.18 |
| Sensation.Avoiding | | | | | | | | | | | | | | | | | | 0.74 | 0.5 |
| Sensory.Sensitivity | | | | | | | | | | | | | | | | | | | 0.78 |

**Table 3-18**

*Correlations of Quantitative Sensory Measures with Qualitative Sensory Measures*

| | DD_RF | DD_RP | Detection_RTh | Detection_RF | Detection_RP | Discrim_RTh | Discrim_RF | Discrim_RP | Sensation.Seeking | Sensation.Avoiding | Sensory.Sensitivity | Low.Registration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DD_RTh | 0.59 | 0.25 | -0.24 | -0.06 | -0.1 | -0.13 | 0.19 | 0.29 | 0.11 | -0.02 | 0.01 | 0.07 |
| DD_RF | | 0.38 | -0.23 | -0.08 | 0.04 | -0.13 | 0.29 | 0.2 | 0.21 | -0.16 | -0.14 | -0.11 |
| DD_RP | | | 0.12 | 0.02 | -0.05 | 0.08 | 0.09 | 0.14 | -0.01 | -0.09 | -0.1 | -0.06 |
| Detection_RTh | | | | 0.53 | 0.27 | 0.87 | -0.01 | 0.15 | -0.07 | 0.16 | 0.02 | -0.09 |
| Detection_RF | | | | | 0.24 | 0.37 | 0.56 | 0.2 | 0.25 | 0.26 | 0.09 | -0.01 |
| Detection_RP | | | | | | 0.38 | 0.1 | 0.4 | 0.28 | 0.14 | 0.2 | 0.05 |
| Discrim_RTh | | | | | | | -0.01 | 0.25 | -0.05 | 0.04 | -0.04 | -0.11 |
| Discrim_RF | | | | | | | | 0.06 | 0.31 | 0.05 | 0.01 | 0.04 |
| Discrim_RP | | | | | | | | | 0.2 | 0.08 | 0.27 | 0.16 |
| Sensation.Seeking | | | | | | | | | | -0.11 | 0.04 | 0.18 |
| Sensation.Avoiding | | | | | | | | | | | 0.74 | 0.5 |
| Sensory.Sensitivity | | | | | | | | | | | | 0.78 |

# Chapter 4

# DISCUSSION

## 4.1 Overview

This study examined quantitative clinical somatosensory measures in concert with a visually guided precision grip force task in adults with and without ADHD. The results did not demonstrate differences between adults with and without ADHD for quantitative somatosensory measures. In contrast, the results showed differences for qualitative sensory measures. There were differences found between the groups in three of four subscales of the AASP. Consistent with our first hypothesis, mean force, standard deviation of force, and CoV scaled to target amplitude, such that low amplitudes were characterized by greater variability than high amplitudes. Our second hypothesis predicted tactile threshold-estimates would be correlated with error in low amplitude, but not high amplitude, force conditions. The results showed that this prediction was incorrect. There was no correlation between tests with Von Frey hair monofilaments with error in any amplitude conditions, except on the right palm in the 15% MVC and 40% MVC conditions. With respect to the third hypothesis regarding the relationship between force and somatosensory deficits, the results showed a correlation only in the off-rate condition. Participants who had a faster decrease in force had larger detection threshold estimates on the right thumb and right finger. Adults with ADHD placed less pins than adults without ADHD in the Purdue Pegboard test. Overall, these findings suggest that if adults with ADHD have somatosensory deficits, they are likely on the scale of smaller spatial resolution than we tested. These clinical somatosensory measures are not sensitive enough to detect differences in young adults with and without ADHD. I will first discuss the results for the somatosensory assessments, followed by the AASP and motor tasks and finally the related measures correlations.

## 4.2 Somatosensory Tests

There were no differences between adults with and without ADHD for the two-point discrimination-threshold estimates, tactile detection-threshold estimates, and the tactile discrimination-threshold estimates assessments. When looking at the two-point discrimination threshold estimates, the lack of a significant difference between groups may be due to the lower limit of the disk used in our study. Specifically, the 1mm distance between the points may be too large to determine the differences. Previous work has shown that children with ADHD have tactile deficits processing repetitive tactile information, reaction time tasks, static detection threshold, and simultaneous frequency test (N. A. Puts et al., 2013). In a subsequent study, Puts et al. (2017) used more advanced and precise tactile measurements by using a four-digit tactile stimulator custom-built by Cortical Metrics (Semora, NC). This device was used to apply small changes of frequency, whereas we used Von Frey Filaments, which applied larger force changes between trials. Von Frey hair monofilaments have not previously been used to assess the tactile differences in adults with ADHD. One explanation for the lack of difference between groups is that this clinical test is not sensitive enough to detect more subtle differences.

## 4.3 Adult Adolescent Sensory Profile

Adults with ADHD scored significantly higher in the Low Registration, Sensation Avoiding, and Sensory Sensitivity sections of the AASP, indicating that adults with ADHD are more sensitive to and aware of sensory stimuli. There was no significant difference between the groups in the Sensation Seeking category. Clince, Connolly, and Nolan (2016) administered the AASP to students over the age of 18 with ADHD or ASD enrolled at one of four higher education institutions. Clince, Connolly, and Nolan report higher scores in the same three categories for adults with ADHD and adults with ASD as we do. Clince et al. found lower scores for the ADHD and ASD groups in Sensation Seeking whereas we found no difference between the ADHD group and the control group in this section. Shimizu et al. (2014) found children with ADHD scored lower in the Sensation Seeking, Sensory Sensitivity, Low Registration and Sensation Avoiding categories of the AASP than control children (V. T. Shimizu et al., 2014). The differing results between our study and Shimizu et al. could be due to the different age groups studied.

### 4.4 Motor tests

In contrast to our previous work (Neely et al 2016, Neely et al 2017), adults with ADHD did not produce more force than adults without ADHD, for all seven amplitude conditions. In a review of gender differences and ADHD, it was observed that men tend to display hyperactivity and impulsivity symptoms more than women do. However, females displayed more innattention than men. Also, in children, motor function deficits were seen more in boys with ADHD than girls (Rucklidge, 2010). Since the current study had a smaller proportion of male participants than the previous study, this could explain the differences seen in force produciton. The current study found that adults with ADHD placed less pins in the Purdue Pegboard task than adults without ADHD. A different study by Pitcher et al. demonstrated that male children with ADHD did not differ in the amount of pegs placed with the right hand when compared to male children without ADHD (Pitcher, Piek, & Hay, 2003). However, another study involving both male and female children found significant differences in the amount of pegs placed with the dominant hand (Ayaz, Ayaz, Yazgan, & Akin, 2013). The differences seen between these two studies could involve participant's sex. Our results agreed with the second study, which could indicate that the motor deficits assessed by the Purdue Pegboard task do not change with age, and are persistent into adulthood.

**4.5 Related Measures**

Bivariate correlations were conducted to evaluate relationships between motor and somatosensory tests. The pattern of high scores Sensation Avoiding, Sensory Sensitivity, and Low Registration positively correlating with high scores on the CAARS demonstrates that with increased awareness of sensory stimuli the more ADHD symptoms one may present. High scores on Low Registration could explain why ADHD students enjoy having background noise when studying (Clince et al., 2016). The fact that Sensation Seeking was not different between the groups could indicate that people with ADHD are already hyper-sensitive and do not go out of their way to get additional sensory stimuli. The consistent negative correlation between on-rate and ADHD symptomology indicates that those who were slower to get to the target reported more ADHD symptoms. This may be attributed to difficulty attending to the task or difficulty following instructions. Participants were instructed to move the colored bar to the target bar as quickly and accurately as possible. A previous study using a similar precision grip task showed that adults with ADHD were more accurate than adults without ADHD (Neely et al. 2016). This could indicate that participants with ADHD focus more on accuracy than quickness. There was no correlation between off-rate and ADHD symptomology. A positive correlation between root mean square error and the hyperactivity/ restlessness score on the CAARS was observed for the 20% MVC condition. Root mean square error in all other amplitude conditions was not correlated with CAARS, indicating that root mean square error is not reliably associated with ADHD-related symptoms. Correlations in three out of the seven amplitude conditions were observed for CoV with tactile discrimination-threshold estimates, indicating that somatosensation on the right thumb may influence the mean and standard deviation of force output. Specifically, the higher the tactile discrimination-threshold estimates the greater the CoV. Low Registration was negatively correlated with on-rate in the three of the seven amplitude conditions. Low registration is defined as missing stimuli or taking longer to respond to stimuli. The slower the on-rate the higher participants scored in the Low Registration section of the AASP. This shows that they have a passive response to the cue to produce force. Off-rate was consistently negatively correlated with somatosensory measures. This indicates that the faster the rate of force decrease, the higher somatosensory measurements were. Off-rate may be related to poor somatosensation. No consistent correlations between quantitative sensory measures with qualitative sensory measures were observed. This could be explained by the fact that the quantitative sensory measures only investigated somatosenation, but the qualitative sensory measures investigated all five senses.

**4.6 Limitations and Conclusions**

The Limitations of this study include the manual application of Von Frey hairs. The duration time the Von Frey hair was applied to on the finger was not regulated, and this could affect the discrimination-threshold estimate. For instance, if the Von Frey hair was applied for a longer period of time, participants may associate this additional time with it being a stronger force. Also, Von Frey hairs may fatigue (Lambert, Mallos, & Zagami, 2009) based on the temperature and humidity in the environment. Last, the current study needs more male participants, because of the potential of gender differences.

The goal of this work was to study somatosensation in concert with motor tasks, to examine possible relations between the two. The results demonstrated there were no differences between the individuals with and without ADHD on the somatosensory tests, suggesting that the clinical measures may not be sensitive enough to detect differences in this sample. Further, no differences were revealed for dependent measures from the seven amplitude conditions. However, the individuals with ADHD placed significantly less pins than the adults without ADHD on the Purdue Pegboard task. In general, individuals that self-report more ADHD-related symptoms report greater sensitivity to sensory stimuli as measured by the AASP. Surprisingly, no association between the self-reported sensory sensitivity (i.e., AASP) and quantitative measures of somatosensation were observed. In terms of the force task, participants that had fast rate of decrease of force from the target had worse tactile detection. This finding suggests that rate of force decrease may be related to poor somatosensation at the index finger and thumb. Future studies should examine smaller force amplitudes under 10% MVC and somatosensation tests with greater resolution because subtle differences may exist, that went undetected in the current study. Further, large sample sizes for such work should be obtained to better reflect the characteristics (e.g., variability) of the population.

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# ACADEMIC VITA

**Academic Vita of Jacqueline Tucker**
Jrt5329@psu.edu

**EDUCATION:**

Major: Bachelor of Science in Biomedical Engineering
*The Pennsylvania State University*, University Park, PA Schreyer Honors College
Graduation: May 2018

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**RESEARCH:**

**Senior Undergraduate Research Assistant**
***Penn State Brain and Behavior Lab*** 01/2015-Present

- Responsible for data collection of behavioral and neuroimaging human subjects experiments
- Manage and oversee post-processing of time-series data in MATLAB
- Assist with the preparation of figures for manuscripts and posters
- Assist with data management in SPSS
- Assist with day-to-day operations of the laboratory including recruitment, sample deliveries, and administrative tasks

**Research Assistant**
***Laboratory of In Vivo Reprogramming*** 08/2016-10/2016

- Completed a research study on an AAV virus and neuron regeneration
- Performed immunostaining and took images of mouse brains using microscopes

**Research Intern**
***The Pennsylvania State Hershey Medical Center*** 05/2016-08/2016

- Tested if an AAV virus expressing NeuroD1 improved motor function post stroke
- Performed injections of the treatment into mouse brains and conducted behavioral tests
- Presented research through a poster and oral presentation at the Undergraduate Symposium

**Research Intern**
***Nemours/ Alfred I. DuPont Hospital for Children*** 06/2015-08/ 2015

- Conducted research on macrocephaly and subdural collections in infant brains
- Measured subarachnoid space by looking at MRI, CT, and ultrasounds of human brains
- Met with patients in addition to observing and shadowing doctors
- Presented work at the Delaware INBRE Summer Undergraduate Symposium

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**PUBLISHED MANUSCRIPTS:**

Neely, K.A., Wang, P., Chennavasin, A., Samimy, S., **Tucker, J.,** Merida, A., Perez-Edgar, K. HuangPollock, C. “Deficits in inhibitory force control in young adults with ADHD.” Neuropsychologia 99 (2017): 172-178.

**Tucker, J.**, Choudhary, A, Piatt, J. "Macrocephaly in infancy: benign enlargement of the subarachnoid spaces and subdural collections."Journal of Neurosurgery: Pediatrics 18.1 (2016): 16-20.

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**CONFERENCE PRESENTATIONS:**

Mookerjee, S. , Kim, D., Neely, K.A, **Tucker, J.**, Somani, Y., Flanagan, M., Kim-Shapiro, D., Basu, S., Proctor, D. FACSM. *Nitrate Supplementation Influences*

*Contraction-Relaxation Rates during Ischemic Exercise in Post-Menopausal Women*. Abstract submitted for the annual meeting of the American College of Sports Medicine Conference.

**Tucker, J.,** Merida, A., Dahm, C.R., Groff, A.J., Wang, P., Etter, N.M., Neely, K.A. *Self-reported sensory perception is related to precision grip force in healthy young adults.* Abstract presented at the annual meeting of the Society for Neuroscience.

Wang, P., Chennavasin, A., **Tucker, J.**, Samimy, S., Reynolds, M., Huang-Pollock, C., Neely, K.A. (2016, October). *Deficits in inhibitory force control in young adults with ADHD.* Abstract presented at the annual meeting of the Society for Neuroscience.

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**COMMUNITY INVOLVEMENT:**

***Volunteer, Mount Nittany Medical Center*** 11/2015–Present
- Transport patients to ultrasound, CT and MRI scans in the emergency department
- Deliver medical devices to patients and assist with any needs the doctors have

***Vice President, Global Brigades*** 09/2014-Present
- Traveled to Central America and worked in medical clinics alongside doctors
- Lead a brigade of 25 volunteers to Nicaragua in May 2017
- Organized a trip leader workshop for all trip leaders in the organization at Penn State
- Budget, keep records and allocate Global Medical Brigades funds

***Member, Penn State Club Cross Country* team** 09/2014-Present
- Participate in practices three times a week and meets

***Tutor, PSUKnowHow*** 11/2015-05/ 2016
- Conducted private tutoring sessions for math, chemistry, and physics
- Prepared practice problems and reviews for tutoring sessions

***Volunteer, American Red Cross*** 10/2015-05/2016
- Answered phone calls at the front desk and directed guests
- Assisted in check-in and other tasks at various blood drives

***Member, Phi Eta Sigma Honor Society*** 03/2014-05/2015
- Attended meetings and suggest ideas for future activities
- Volunteered at several events including bingo with the elderly

***Catering Associate*** 11/2014 - 05/2015
- Prepared menus and meals for on campus catering events
- Managed work space organization with a team of seven people

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**HONORS:**

College of Engineering Research Experience Spring 2018
Dean's List Fall 2014-Present
Undergraduate Research Travel Grant November 2017
Erickson Discovery Grant April 2017
President's Award Fall 2014