Degree project

HÖGSKOLAN
I SKÖVDE

Inhibitory Control in Adults with ADHD

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Abstract

Inhibitory control refers to a person's ability to control responses and impulses. Deficits in inhibitory control have been found in the neurodevelopmental disorder of Attention deficit hyperactivity disorder (ADHD), though this has mainly been studied in children. This thesis is a systematic review of how inhibition is impacted in adults with ADHD and which neural correlates that are associated with inhibitory control. Only peer-reviewed original articles that used adults above the age of 18 were included. All articles used a between subject design, meaning healthy participants were compared to participants with ADHD. To measure inhibitory control, articles which used either the Stroop Task or Go/No-go task were examined. Nine articles were included in this systematic review. Through functional magnetic resonance imaging (fMRI) altered neural activation was seen in several brain regions, such as the dorsolateral prefrontal cortex, fronto-basal ganglia networks, anterior cingulate cortex, posterior cingulate cortex, parietal lobe and inferior frontal gyrus. Many of these regions have previously been linked to inhibitory control, while others hint at possible compensatory pathways for inhibition in ADHD. In summary, subtle impairments in inhibition networks appear to underlie the disorder all the way into adulthood.

Keywords: adhd, inhibition, fmri, inhibitory control

Inhibitory Control in Adults with ADHD

Introduction

We are all encouraged to think before we act. Our capacity to control our impulses and resist acting upon them impacts the way we interact with the world around us. Inhibitory control is a core executive function which refers to our ability to control automatic urges such as behaviors, emotions, attention and thoughts (Kang et al., 2022). Altered functioning in inhibitory control systems can be found in children, elderly and disorders such as substance abuse, conduct disorders and Attention Deficit Hyperactivity Disorder (ADHD) (Munakata et al., 2011). The relationship between ADHD and inhibitory control has primarily been researched in studies with children. ADHD is a neurodevelopmental disorder characterized by difficulties with cognitive processes such as executive functioning, concentration, behavioral impulsivity as well as restlessness (Tripp & Wickens, 2009). For long it was believed that ADHD occurs primarily in childhood and remits in adolescence, though this theory has since been disproved (Biederman et al., 2010). An increase in the prevalence of ADHD diagnoses in adults has been observed in more recent years (Chung et al., 2019). Recent surveys conducted by the World Mental Health Surveys which included 20 countries showed that the rate of ADHD in adults was at approximately 2.8% (Fayyad et al., 2017). Deficits in inhibitory control in children with ADHD has been growing increasing evidence (Gow et al., 2012; Inoue et al., 2012; Lipszyc & Schachar, 2010), but insofar the research on this topic remains scarce concerning the adult population of people with the aforementioned disorder.

The aim of this systematic review is to gain a more in depth understanding of how adults with ADHD are impacted by inhibitory control. The author hypothesizes that adults with ADHD will perform worse than neurotypicals on inhibitory control tasks and display differences in brain functioning compared to neurotypicals during inhibitory control processes. The thesis will begin with an overview of inhibitory control, the neural mechanisms underlying it and then proceed to discuss ADHD as the neural correlates of it as well. The systematic review will then continue to discuss the process of selecting studies to review. The main section will present the results of nine selected studies and their findings regarding inhibitory control in adults with ADHD. To conclude, the thesis will end with a discussion of the results and potential limitations of the paper. Lastly, a conclusion will be made within the discussion.

Inhibitory Control

Inhibitory control does not relate to one specific executive function, rather it consists of several components (Munakata et al., 2011). Having an intact ability of inhibition ensures that a person's behaviors are aligned with their motivations and intentions, whereas compromised inhibitory control results in impulsive responses and actions (Kang et al., 2022). Rather than referring to one single executive function, inhibitory control is composed of several components (Mirabella, 2021; Tiego et al., 2018). Inhibitory control develops from childhood to adolescence and into adulthood as the prefrontal cortex matures (Kang et al., 2022) Inhibitory control can be categorized into interference and motor inhibition. The former regards reaction to conflicts in stimulus as well as error-related response inhibition. The latter concerns the ability to inhibit preplanned motor responses. Motor inhibition can be divided into reactive and proactive types, where reactive refers to the ability to halt a reaction and proactive regards the adaptation of a motor approach depending on context (Mirabella, 2021). Motor inhibition is typically assessed using the Go/No-go task or stop-signal task. The Go/No-go task demands its participants to respond to stimuli by performing or inhibiting a motor response (Congdon et al., 2012). In contrast, interference inhibition is assessed mainly by the Stroop Task. The Stroop Task works by having its participants react to congruent and incongruent trials. The names of colors are presented in different colors of ink and the participants are expected to report the color of ink while ignoring the name of the color. When the name of the color and the color of ink are congruent, participants tend to respond more correctly and quickly than when they are incongruent (Kang et al., 2022).

When examining task performance, interference and facilitation are factors to consider. Interference and facilitation provide insight into the degree to which participants struggle to comply with task demands and focus on the word rather than the color of ink. Interference refers to the percentage of increase in slowed reaction time on incongruent trials in comparison to neutral trials. By contrast, facilitation is the increase in percentage of speeded reaction time on congruent trials compared to neutral trials. Further, within-block and across-block analyses are made. A within-block analysis considers the reaction time for a block specific trial type (congruent or incongruent) compared to neutral trials within said block. However, an across block analysis compares the mean reaction time of all the trials within a block to the neutral block (MacLeod, 1991).

Neural correlates of inhibitory Control

There are two generally accepted theories of inhibitory control, one which supports the idea of a modular perspective and another which promotes a more global network. (Aron et al., 2014). According to the modular perspective, behavioral inhibition is correlated with the specific brain region of the right inferior frontal gyrus. The right inferior frontal gyrus is considered to interact with fronto-basal ganglia networks which can be divided into different modes of inhibition (Aron et al., 2003). In opposition to this theory, the network perspective considers inhibitory control to be supported by more general regions including the frontal multiple-demand cortex (Duncan, 2010). fMRI data has shown that the right inferior frontal gyrus and anterior insula are involved in tasks such as Go/No-go task (Kang et al., 2022). Damage to those areas is associated with poor motor inhibition (Hampshire & Sharp, 2015). The insula is involved in performance monitoring and consciously perceived errors (Ullsperger et al., 2010). Poor self regulation and inhibitory control has been considered to be influenced by deficits in error processing (Shiels & Hawk, 2010). The modular view reduces inhibitory control to a discrete cognitive function where the right inferior frontal gyrus sends projections to the subthalamic nucleus to inhibit motor processes (Coxon et al., 2006). However, some studies suggest that the right inferior frontal gyrus is mainly defined by the ability to maintain task relevant information based on response initiation as well as in response inhibition. This is because the right inferior frontal gyrus is involved in monitoring the environment for stimuli (Munakata et al., 2011).

In contrast, the viewpoint of an inhibitory network proposes that the fronto-multiple-demand cortex extendeds to numerous subcortical brain areas. It states that inhibitory control cannot be neurally represented by only one brain region, but rather relies on multiple networks (Kang et al., 2022). One study found that successful inhibitory responses in adults were linked to increases in activation in the ventrolateral prefrontal cortex, the right parietal lobe and right dorsolateral prefrontal cortex regions (Durston et al., 2002).

An fMRI study observed that motor inhibition in children and adults was correlated with enhanced activity of the right fronto-basal ganglia network (Schel et al., 2014). Compared to adolescents, adults display increased activation in the right prefrontal cortex compared to adolescents in inhibitory control tasks (Rubia et al., 2007). Generally, right frontal prefrontal regions of the brain tend to be important areas for inhibitory processes. The right prefrontal regions are involved in emotional responses and reactions (Hampshire & Sharp, 2015). Systems for different domains of inhibition such as emotional, cognitive and motor appear to vary to some degree whilst also sharing some of the functioning (Banich & Depue, 2015). It has been suggested that the pre-supplementary motor cortex is a determinant in successful response inhibition and modulates the activity in the motor cortex when there is cognitive conflict (Simmonds et al., 2008).

The ability to inhibit emotional responses has been observed to implicate the right superior, middle and frontal gyri and right dorsolateral and ventrolateral region (Frank et al., 2014). fMRI work has found that the right lateral prefrontal cortex is implicated in inhibition of memory retrieval by downregulating the hippocampal activity (Depue et al., 2007).

Further, activation of the middle frontal gyrus has been discovered to predict the degree of success at inhibition of memory retrieval (Banich & Depue, 2015).

The reason behind why a lot of inhibitory control processes are lateralized to the right side of the brain is unclear. The right hemisphere is more associated with avoidance behaviors rather than approach behaviors, as well as important in surveillance of the external environmental context. This is believed to be a potential reason for why inhibitory functioning is lateralized, as it could be linked to an inclination towards controlling avoidance behavior, evaluation of your surroundings and motivation (Hampshire & Sharp, 2015).

ADHD

ADHD is a heterogeneous disorder which presents itself in three different subtypes; inattentive, hyperactive and combined (Mueller et al., 2017). While ADHD is classified into these subtypes, they are mere presentations of the same disorder and the DSM-5 states that the symptomatology can manifest itself differently over time (Cabral et al., 2020). Research with children has displayed that the main domains affected in all of the variations of ADHD are executive function and motivation (Tripp & Wickens, 2009). Individuals living with ADHD show symptoms including deficits in working memory (Martinussen et al., 2005), attention regulation (Kofler et al., 2013), and response inhibition (Crosbie et al., 2013). The disorder is diagnosed by persistent patterns of inattention and impulsivity over a period that extends beyond six months (Mueller et al., 2017). Having ADHD is associated with several problems which affects the individuals academic, work, home and social life. Adolescents with ADHD are at greater risk of not graduating high school or college than their peers, and with increased likelihood of risk taking behaviors, including substance abuse (Cabral et al., 2020). There is an apparent genetic component to the disorder, the heritability of the disorder has been established through numerous twin and family studies (Tripp & Wickens, 2009). Most notably, genetic variations in the dopamine receptors called D4 have been shown to be linked to ADHD (Cabral et al., 2020). ADHD is commonly treated using the drug methylphenidate which acts as agonists on the dopaminergic synapses. One theory proposes that the failure of dopamine cell response to transfer to reward expectations, which would explain some ADHD symptoms (Tripp & Wickens, 2009).

Neural correlates of ADHD

fMRI studies suggest that differences in cortical functional networks play a big role in ADHD (Gao et al., 2019; Sutcubasi et al., 2020). Frontostriatal dysfunction has been found in neuroimaging studies with ADHD patients. It has been hypothesized that the fronto-dorsal striatal circuit is responsible for cognitive dysfunction, meanwhile the fronto-ventral striatal circuit is responsible for motivational dysfunction in individuals with ADHD (Shen et al., 2020). The ventral striatum has been associated with reward processing. Children with ADHD have been observed to have increased symptoms of impulsivity in correlation to having reductions in volume of the ventral striatum (Carmona et al., 2009). Another study with adults showed hypoactivation of the ventral striatum to rewards in adults with ADHD (Plichta et al., 2009). Decreases in blood flow in regions of dopamine transporter binding and the striatum is prevalent in ADHD (Tripp & Wickens, 2009).

Reduced volume of several brain regions and overall brain size has been found to persist into adolescence for people with ADHD in several studies (Tripp & Wickens, 2009). The dimensions of the caudate nucleus, corpus callosum and cerebellar vermis have been observed to be reduced in volume in those with ADHD (Valera et al., 2007). Further, structural abnormalities in the right prefrontal cortex, insula and basal ganglia have been reported in ADHD (Shen et al., 2020). Areas containing high densities of dopamine receptors are smaller in people with ADHD compared to healthy controls, such as the caudate nucleus and globus pallidus (Swanson et al., 2007). Studies have found that dorsal striatum dopamine receptor activation has been correlated with response inhibition (Robertson et al., 2015). Moreover, working memory performance has also been correlated with dopamine activity nuclei and prefrontal cortex activity (D'Ardenne et al., 2012). Lower gray matter volume of the posterior occipital cortex has been positively correlated with ADHD and symptoms of inattention (Shen et al., 2020). Further, hyperactivation and having higher gray matter volume in the posterior occipital cortex is correlated with a preference for delayed gratification above immediate rewards (Owens et al., 2017).

In measuring cognitive control, emotional processing and reward tasks, those with ADHD have displayed enhanced activation in the default mode network (DMN) (Cortese et al., 2012). An inability to deactivate the DMN has been inversely correlated with hypoactivation of the fronto-striatal regions. The DMN engages areas such as the posterior cingulate cortex, medial prefrontal cortex and precuneus (Vatansever et al., 2015). These findings reinforce what is known about ADHD and distractibility in combination with poor task performance (Christakou et al., 2013). Additionally, volume reductions limbic regions like the amygdala and hippocampus have been observed in people with ADHD (Hoogman et al., 2017). Lastly, abnormal activation of fronto-limbic areas has been observed in ADHD (Spencer et al., 2017). The study by Spencer et al. (2017) found hyperactivation of the insula and hippocampus and underactivation of the ventromedial prefrontal cortex and dorsal anterior cingulate cortex in ways that are reminiscent of people living with post traumatic stress disorder. The anterior cingulate cortex plays a key role in feedback monitoring, error awareness and response inhibition (Menon & Uddin, 2010).

The aim of this systematic review

The aim of this systematic review is to further explore the relationship between inhibitory control and ADHD in adults and to gain deeper insight into the neural mechanisms involved. Inhibitory control is assessed using different cognitive tasks such as the Stroop Task and the Go/No-go task (Munakata et al., 2011). This systematic review will examine how adults with ADHD perform on these cognitive tasks in comparison to their neurotypical peers, while considering fMRI data to understand the neural underpinnings.

Methods

Search strategy

The selected sample of studies was obtained through a literature search using the electronic databases Scopus and Web of Science. The final search strings were “ADHD” AND “Inhibitory control” AND “Adult” AND “fMRI” AND “Stroop Task”, as well as “ADHD” AND “Go/No go Task” AND “Inhibitory control” AND “Adults” and “fMRI”. Alternate versions of the search strings were included, which has the complete names without abbreviations. “Attention Deficit Hyperactivity Disorder” AND “Inhibitory control” AND “Adult” AND “Functional resonant magnetic imaging” AND “Stroop Task”, as well as “Attention Deficit Hyperactivity Disorder” AND “Go/No go Task” AND “Inhibitory control” AND “Adults” and “Functional resonant magnetic imaging”. Initially a total of 28 articles were identified. After controlling for duplicates three articles were removed and 25 remained. Post screening the articles there were 13 reports left to assess for eligibility. Three articles were removed due to not meeting the inclusion criterions. Finally, nine articles remained to be utilized in the systematic review. The final search was done on the 27th of February 2023.

Inclusion & exclusion criteria

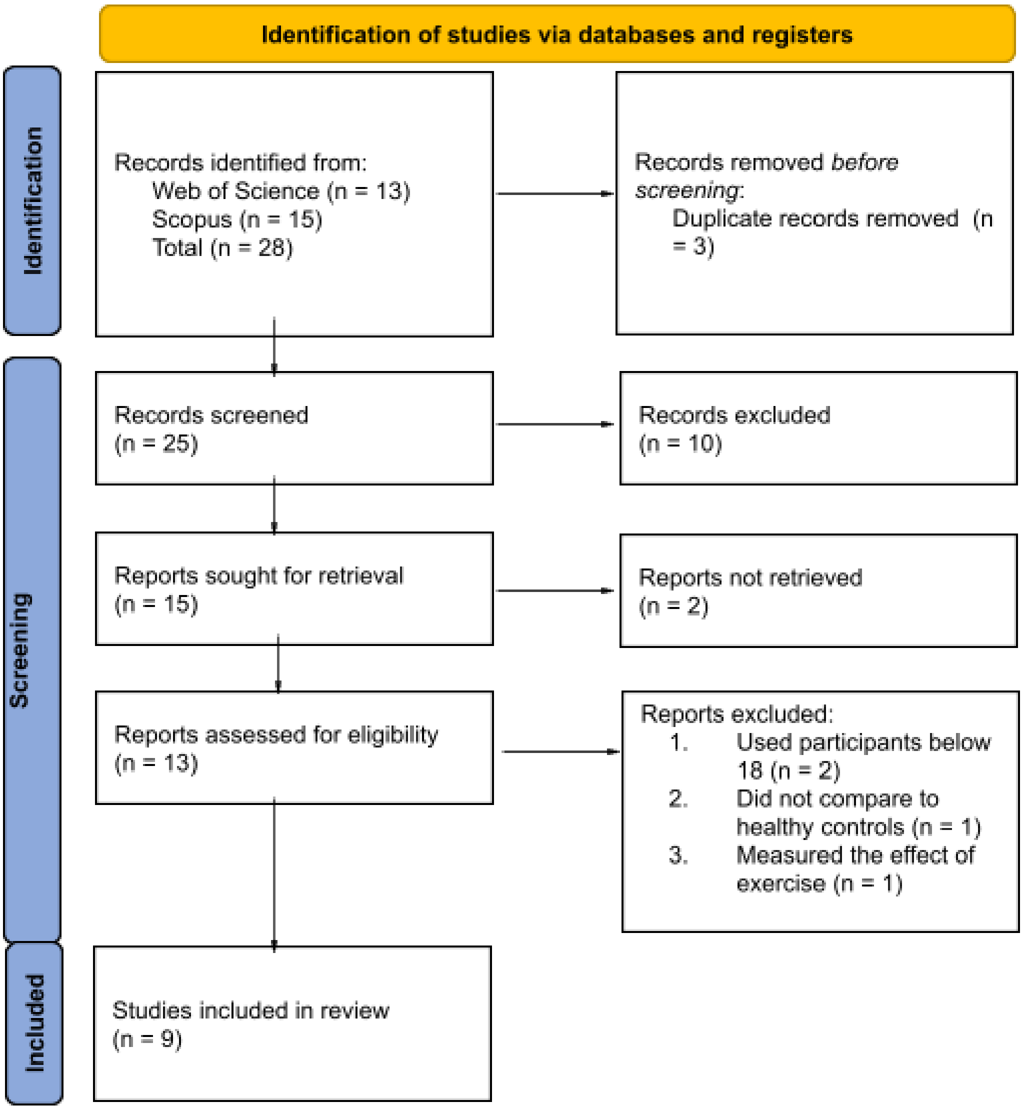
This systematic review included studies with both female and male participants above the age of 18. Only original articles written in English were included. All articles were published in peer-reviewed journals. Articles using participants who were actively taking stimulant medication for their ADHD were excluded as this could impact the performance on the different tasks. As this systematic review subscribes to a between-subject design, only articles which compared ADHD participants to healthy controls were eligible for inclusion. To gain insight into interference and motor inhibition, articles using both the Stroop task and Go/No-go task were included. A final inclusion criteria was articles which included all types of attention deficit disorders, meaning impulsive, inattentive and combined variations. Some articles were excluded for the reasons of including children or testing for another variable, such as the effect of exercise on the performance of inhibitory control tasks. Lastly, a few articles were excluded for not using fMRI.

Data extraction

Data for outcome measurements such as fMRI results and accuracy score of inhibitory tasks and main findings will be extracted. Sample characteristics will be extracted such as age, intervention group and control group.

Flow chart

Fig. 2 PRISMA Flow chart



Note. Presentation of the study selection process illustrated within a PRISMA flow chart (Page et al., 2021).

Table 1

Characteristics of Included Studies

First Author & publication date	Sample characteristics	Intervention	Outcome measurements	Results
Banich et al. (2009)	N=46 Intervention group=23 Males in intervention group= 14 Age= +18	Color-Word Stroop Task	fMRI Result of Color-Word Stroop task	No differences in task-performance. Heightened activation of the posterior cingulate cortex and insula. Decreased activation of the anterior cingulate cortex, inferior frontal gyrus and dorsolateral prefrontal cortex.
Burgess et al. (2010)	N=43 Intervention group = 20 Male in intervention group = 12 Age, mean (SD) = 20.1 (1.8)	Color-Word Stroop task	fMRI Result of Color-Word Stroop task	No differences in task-performance. Decreased activation of the anterior cingulate cortex, and dorsolateral prefrontal cortex.
Chen et al. (2015)	N=54 Intervention group = 29 Male in intervention group = 29 Age, mean (SD) = 24.3 (2.76)	Go/No-go task	fMRI Results of Go/No-go task	No differences in task-performance. Heightened activation of the thalamus. Decreased activation of the insula and dorsolateral prefrontal cortex.
Depue et al. (2010)	N=46 Intervention group = 23 Male in intervention group = 14 Age, range = 18-23	Color-Word Stroop task	fMRI Result of Color-Word Stroop task	No differences in task-performance. Decreased activation of the anterior cingulate cortex, orbital frontal cortex, the basal ganglia, caudate nucleus, putamen and ventral striatum.

Dillo et al. (2010)	N= 30 Intervention group= 15 Male in intervention group= 11 Age, mean= 28.1	Go/No-Go task	fMRI Results of Go/No-go task	No differences in task-performance. Heightened activation of the parietal lobe and inferior occipital gyrus.
Kooistra et al. (2010)	N=22 Intervention group = 11 Male in intervention group=11 Age, mean = 22.3	Go/No-go task	fMRI Results of Go/No-go task	No differences in task-performance. Heightened activation of the posterior cingulate cortex and anterior cingulate cortex.
Mulligan et al. (2011)	N=24 Intervention group = 12 Male in intervention group=12 Age, mean (SD) = 31.6 (2.5)	Go/No-go task	fMRI Results of Go/No-go task	No differences in task-performance. Decreased activation of the pre supplementary motor cortex and inferior parietal lobe.
Schulz et al. (2014)	N=28 Intervention group = 14 Male in intervention group = 28 Age, mean (SD) = 23.3 (2.3)	Face emotion Go/No-go task	MRI Results of Face emotion Go/No-go task	The ADHD group performed worse. Participants with ADHD had increased dorsolateral prefrontal cortex connectivity with the bilateral fusiform face area.
Shang et al. (2018)	N= 80 Intervention group: 50 Male in intervention group = 26 Age, mean =28.82	Counting Stroop Task	fMRI Results of counting Stroop Task	The ADHD group performed worse. Decreased activation of the inferior frontal gyrus, caudate nucleus and superior parietal lobe.

Results

Most of the studies included young adults with the mean age of between 20 and 28. One study included older participants. The studies had a total of 373 participants , 211 participants in intervention groups and 162 participants in control groups. The gender of participants in total was 58% male and 42% female and in most of the studies the genders were equally distributed. Four of the studies had a big majority of male participants (Banich et al., 2009; Burgess et al., 2010; Depue et al., 2010; Dillo et al., 2010), and one study only included males (Schulz et al., 2014).

Stroop Task Performance results

Interference scores, both across and within blocks, were lower for the ADHD participant group than the healthy controls in the study by Banich et al. (2009). Across blocks the ADHD group and the control group had an interference that was significant, but the interference for within block results were greater for both the ADHD group and for the control group as well (Banich et al., 2009). Burgess et al. (2010) came to similar conclusions. Interference scores across and within block trials were greater for controls compared to participants with ADHD. However, Shang et al. (2018) discovered greater interference for the participants with ADHD compared to controls.

Further, the ADHD group displayed increased facilitation within and across blocks as according to Banich et al. (2009). Within block facilitation was .5% for participants with ADHD and -.4.3% for controls. Across block facilitation was 1.7% for participants with ADHD and −0.6% for controls (Banich et al., 2009). This is in alignment with the results in the study by Burgess et al. (2010). In the study facilitation was revealed to be greater for the ADHD group compared to controls. Shang et al. (2018) found that the ADHD groups had a longer reaction time on congruent tasks as well, meaning that the facilitation was greater for the controls. Likewise, Depue et al. (2010) noticed that participants with ADHD had a longer reaction time overall. No significant differences in task performance were unveiled by Depue et al. (2010).

The scores for accuracy on task performance yielded no significant differences for participants with ADHD relative to controls in both the study by Banich et al. (2009) and Burgess et al. (2010). However, the study by Shang et al. (2018) discovered less accuracy in the performance of participants with ADHD compared to controls, specifically in the incongruent trials.

fMRI results of the Stroop Task

The four articles which utilized the Stroop Task as a means of measuring inhibitory control found some overlapping and some unique results regarding brain activation. Banich et al. (2009) found that when the ink color was to be selected above reading the word, participants with ADHD displayed less activity in the left posterior and left middle dorsolateral prefrontal cortex as compared to controls. Similarly, Burgess et al. (2010) found that the posterior dorsolateral prefrontal cortex had increased activation during incongruent and congruent blocked conditions, but not neutral conditions, for the control group.

Further, Banich et al. (2009) observed that across all three conditions, the participants with ADHD had increased activity in the right insula, posterior cingulate cortex and bilateral superior temporal gyri. Controls had greater inferior frontal gyrus activity (Banich et al., 2009). Results from the same article also revealed that incongruent block trials compared to neutral trials were synonymous with increased brain activity in the thalamus and anterior cingulate cortex for the control group. Simultaneously Burgess et al. (2010) found that incongruent trials were associated with hypoactivation of the dorsal anterior cingulate cortex in the ADHD group.

Both Burgess et al. (2010) and Banich et al. (2009) discovered increased activity in the left precuneus for controls during congruent blocks. Banich et al. (2009) specifically observed heightened activity in the left precuneus and left inferior parietal lobule during both congruent and incongruent blocks. During both congruent and incongruent blocks the ADHD group activated the right middle frontal gyrus to a higher degree than controls (Banich et al., 2009).

Burgess et al. (2010) observed that healthy controls also displayed greater activation of the precuneus, left angular gyrus and right dorsolateral prefrontal cortex during blocked contrast of congruent and neutral trials (Burgess et al., 2010).

The findings of Shang et al. (2018) showed abnormal activational patterns in different brain regions. The caudate nucleus, inferior frontal gyrus and superior parietal lobe were all implicated in the fMRI results for healthy participants and the participants with ADHD. The aforementioned regions had heightened activation in the congruent versus incongruent trials in healthy controls. Individuals with inattentive ADHD had hypoactivation in the caudate nucleus and inferior frontal gyrus compared to controls. Those with combined-type ADHD also displayed decreased activations in those regions and decreased activity in the superior parietal lobe as well.

Depue et al. (2010) observed alterations in neural action in numerous brain areas, such as the lateral prefrontal cortex, inferior frontal cortex, anterior cingulate cortex, orbital frontal cortex, the basal ganglia, caudate nucleus, putamen, ventral striatum and cerebellum. Said regions appeared to be negatively correlated with the severity of inattention and reaction time in people with ADHD. However these regions were not correlated with hyperactivity.

Go/No-go Task performance results

The performance results on Go/No-go tasks did not differ greatly in the majority of the studies. Chen et al. (2015), Dillo et al. (2010), Kooistra et al. (2010) and Mulligan et al. (2011) all found no differences in error performance for the intervention group in contrast to controls. Schulz et al. (2014) on the other hand, discovered dissimilarities between groups. Both during “Go” and “No-go” trials, participants with ADHD made fewer correct inhibitions and responses (Schulz et al., 2014) . Reaction time did not vary between groups in any of the studies, besides Kooistra et al. (2010). This study found that the ADHD group were slower to respond than controls. The study by Chen et al. (2015) measured self-perceived difficulty after taking the task, and the participants with ADHD found the Go/No-go task to be more difficult than controls.

fMRI results for the Go/No-go task

During successful response inhibition, both participants with and without ADHD displayed activation of the bilateral anterior cingulate cortices and parahippocampus in the study by Chen et al. (2015). During this condition, participants with ADHD activated the right inferior frontal lobe, fusiform gyrus and left supramarginal parietal lobe, whilst healthy controls activated the left inferior frontal lobe and right precuneus (Chen et al., 2015). Unlike the other studies, Chen et al. (2015) observed that activation of the insula was linked to both successful response inhibition and error processing for both the experimental and control group. However, the frontoinsular cortex had a higher degree of activation in error related processing for the participants with ADHD. Schulz et al. (2014) found that correct no-go responses were neurally correlated with greater activity in the left inferior gyrus and left putamen as well as right dorsolateral prefrontal cortex and bilateral subgenual cingulate cortex in control subject as contrasted with the neurodivergent participants. However both groups did have increased right inferior frontal gyrus, right dorsolateral prefrontal cortex, right middle temporal gyrus and right fusiform face area activation during no-go events compared to the go-events (Schulz et al., 2014). Further the functional connectivity between the dorsolateral prefrontal cortex and limbic areas such as the putamen, sugenual cingulate cortex and inferior frontal gyrus was greater for controls. Participants with ADHD displayed greater functional connectivity between the dorsolateral prefrontal cortex and the fusiform face area (Schulz et al., 2014).

During correct no-go trials the control group demonstrated a higher degree of activation of the right angular gyrus and anterior insula than the experimental group in the study by Mulligan et al. (2011). Further, the same study observed that successful response inhibition in healthy controls had greater degree of brain activity in the right frontal eye field, right pre-supplementary motor area, right- as well as left- inferior parietal lobe, left precuneus and left precentral gyrus (Mulligan et al., 2011). Kooistra et al. (2010) measured both fast and slow Go/No-go conditions. During the slow, No-go condition, the ADHD group displayed an increase in neural action in the following regions: anterior and posterior cingulate gyri, dorsal caudate nucleus, posterior putamen, medial thalamus and frontal gyri. The healthy controls displayed similar activation patterns, only reversely during the slow, Go condition. Kooistra et al. (2010) witnessed heightened anterior cingulate gyri and supramarginal gyri activation during the fast condition No-go trials, but only for the ADHD population. The control group also demonstrated elevated activity in these regions, however, during the Go-trials (Kooistra et al., 2010). In the study by Dillo et al. (2010), the no-go condition implicated regions of the anterior cingulate cortex for both groups. Further, the ADHD participants displayed amplified neural arousal in the parietal cortex, specifically the superior and inferior parietal lobe, as compared to the control group. The ADHD groups also activated the medial and inferior occipital gyrus to an extent that was unmatched by controls. During the Go/no-go task, both groups activated the medial frontal gyrus and anterior cingulate cortex (Dillo et al., 2010).

Chen et al. (2015) measured the neural patterns during error processing. The ADHD group and control group exhibited amplified activity bilateral insula/inferior frontal lobe, anterior cingulate cortex and superior temporal lobe during error processing. The ADHD group also relied upon the right middle temporal lobe, angular gyrus, left supramarginal parietal lobe and thalamus, whereas controls utilized the precuneus and left dorsolateral prefrontal cortex (Chen et al., 2015).

Mulligan et al. (2011) did not detect any brain regions in which the participants with ADHD displayed significantly heightened activation. Both groups activated the right inferior frontal gyrus.

The study by Schulz et al. (2014) showed that both the comparison subjects and participants with ADHD had significant dorsolateral prefrontal cortex connectivity with the bilateral fusiform face area.

Discussion

Main findings

One key finding of the systematic review was that accuracy scores on both the Stroop Task and Go/No-go task didn't differ significantly between the experimental group and control group in seven of the nine articles. In several articles, inappropriate activation of inhibitory structures such as the dorsolateral prefrontal cortex, posterior and anterior cingulate cortex, insula as well as the inferior frontal gyrus was prevalent in adults with ADHD. Primarily, adults with ADHD failed to activate the regions involved in inhibition to the same extent as controls. Lastly, some of the studies found abnormal neural patterns in adults with ADHD, which hints at compensatory neural pathways for inhibition.

The aim of the study was to gain deeper insight into how ADHD is impacted by inhibitory control. It was hypothesized that people with the disorder would perform worse on the inhibitory control tasks. This was incorrect, as most of the studies affirmed the opposite. More so, participants with ADHD were hypothesized to display alternate neural functioning during the inhibitory control tasks. This was observed in several studies, for example by Chen et al. (2015), Dillo et al. (2010) and Kooistra et al (2010). The participants with ADHD did not primarily display alternate neural pathways, rather a decrease in activity in inhibitory regions as compared to controls. There was also no coherence between articles for the different brain regions which would be implicated in maintaining inhibitory control for those with ADHD.

Task performance

If the assessed level of inhibitory control would be strictly determined by the absence of errors in performance, both participants with and without ADHD would have attained similar levels of inhibition for the Go/No-go task, as Chen et al. (2015), Dillo et al. (2010), Kooistra et al. (2010) and Mulligan et al. (2011) all found no significant differences in error performance nor reaction time. Only the study by Schulz et al. (2014), which relied upon the face-emotion version of the Go/no-go task, did discover that participants with the neurodivergent disorder performed worse on the task. This could signify that specific elements of the face-emotion Go/no-go task impacts the inhibitory mechanisms in ADHD differently than the standard version of the task as it investigates how aspects of emotional bias impacts inhibition. Regarding interference inhibition, information unearthed from studies using the Stroop Task, lead to similar discoveries. Only Shang et al. (2018) found that participants with ADHD performed worse and this was the only study using the counting Stroop Task, instead of the standard Color Word Stroop Task.

Posterior cingulate cortex

A noteworthy finding by Shan et al. (2018) is the hyperactivation of the posterior cingulate cortex in adults with ADHD. Heightened posterior cingulate cortex activation in participants with ADHD also indicates improper use of the DMN network during the task (Vatansever et al., 2015), an area related to the DMN. Regions of the DMN such as the posterior cingulate cortex weren't properly disengaged during the Stroop Task within the study by Banich et al. (2009) as well. Kooistra et al. (2010) found that the ADHD group activated this region disproportionately as well. The remaining six articles mentioned no dysfunction of the posterior cingulate cortex. More so, Banich et al. (2009) argue that the heightened activation in posterior language areas signified processing of task-irrelevant words, thus not complying with task conditions, especially in combination with the increased facilitation for the ADHD group.

Anterior cingulate cortex

Banich et al. (2009) and Burgess et al. (2010) also discovered that areas linked to response inhibition such as anterior cingulate cortex weren't as active in the experimental group, providing additional evidence for inhibitory dysfunction (Menon & Uddin, 2010; Aron et al., 2003). Depue et al. (2010) saw decreases in anterior cingulate cortex activation alike. Out of the four articles reviewing the Stroop Task, it was solely the article by Shang et al. (2018) that provided no results regarding anterior cingulate cortex activation. However, the Go/No-go task studies didn't observe this decrease in activation. The study by Chen et al.

(2015) found no variability between groups as far as anterior cingulate cortex activation was concerned, which indicates no difference in response inhibition. Likewise, Dillo et al. (2010) observed equal degree of anterior cingulate cortex activity in both groups, though. Only Kooistra et al. (2010) on the other hand, witnessed an increase in anterior cingulate gyri for the ADHD population. This could potentially hint at a heightened error awareness (Menon & Uddin, 2010). These findings could highlight an increased importance of feedback monitoring and response inhibition in Stroop Task as compared to the Go/No-go task.

Inferior frontal gyrus

There were no significant differences in activation of the inferior frontal gyrus, which is thought to play a critical role in motor inhibition (Aron et al., 2003), between controls and the experimental group as observed by Mulligan et al. (2011) Chen et al. (2015) and Schulz et al. (2014). Shang et al. (2018) discovered that participants with ADHD had hypoactivation of the inferior frontal gyrus. Banich et al. (2009) also saw a decrease in neural activity in the inferior frontal gyrus for the ADHD group. This also supports the theory of failed inhibitory mechanisms in adults with ADHD. Solely the articles focused on interference inhibition, meaning the ones using the Stroop Task, saw dysfunction of this region. This supports the research claiming that the inferior frontal gyrus is defined by the ability to maintain task relevant information based on response initiation and inhibition (Munakata et al., 2011).

Insula

In two of the five studies with the Go/No-go task, observations regarding insula activity were made. Chen et al. (2015) primarily discovered hypoactivation in areas which are correlated with error processing such as the frontoinsular cortex. However, the frontoinsular cortex had a higher degree of activation in error related processing for the participants with ADHD. The abnormalities in insula functioning could potentially be contributing to subtle impairments in executive functioning, as inhibitory control is thought to be affected by error-processing (Ullsperger et al., 2010; Shiels & Hawk, 2010). Anterior insula reductions seen during stop-signals for the ADHD group by Mulligan et al. (2011). This aligns with research in which poor motor inhibition is a consequence of damage to areas such as the insula (Hampshire & Sharp, 2015).

However, the results of the Stroop task yielded no significant results regarding insula activity, with the exception of Banich et al. (2009). The last-mentioned study observed that across all three conditions, the participants with ADHD had increased activity in the right insula, contradicting the aforementioned results.

Dorsolateral prefrontal cortex

Two articles noted dorsolateral prefrontal cortex dysfunction out of the five which studied the Go/no-go task. One of the main findings was the differences in the dorsolateral prefrontal cortex connectivity, as this cognitive control area was more linked to the face processing in patients with ADHD and more linked to processing limbic networks for healthy controls during the task (Schulz et al., 2014). Schulz et al. (2014) hypothesize that these results point towards limbic dysfunction in those with ADHD, which in turn might impact the level of cognitive control exhibited in emotional contexts. When the facial expressions activate limbic systems in healthy controls, they influence performance by acting as salience cues (Schulz et al., 2014). Chen et al. (2015) found that controls had greater dorsolateral prefrontal cortex activity during error-processing. Two out of four articles using the Stroop-Task studies mentioned dorsolateral prefrontal cortex dysfunction. Banich et al. (2009) and Burgess et al. (2010) saw that controls had increased activity in this region. This supports the idea that dorsolateral prefrontal cortex regions are important in response inhibition (Durston et al., 2002; Frank et al., 2014).

Alternate neural pathways

One reason for the similar performance results in the remaining studies could be that participants use compensatory mechanisms to achieve the same level of inhibition. This is supported by the results indicating different patterns of neural activity in the two groups. Kooistra et al. (2010) put forward the theory of a top-down compensation model in people living with ADHD. To preserve inhibitory control, especially during the slow conditions, demanded increased frontostriatal involvement in those with ADHD, potentially signifying a difficulty with maintaining motor activation levels that match task demands. Further, the increased involvement of the thalamus, which was also seen in ADHD participants during error processing in the study by Chen et al. (2015), might speak to an increased modulation of activation relative to task demands (MacLeod, 1991). Moreover, the absence of between-group neural differentiation in activation throughout the fast condition speaks to another finding. This finding underlines a potential regulatory deficit in ADHD, since fast pacing assists those with ADHD in coping with task demands and generating the right level of motor activity (Kooistra et al., 2010).

In support of the theory by Kooistra et al. (2010), Dillo et al. (2010) proposed that people living with ADHD use alternate, compensatory mechanisms to attain the same level of inhibition. As the experimental group exhibited increased neural activation in several brain regions, including the parietal lobe and medial as well as inferior occipital gyrus, it could imply that they are trying to compensate for their inattention by using alternate compensatory strategies to increase concentration, which would become ineffective when used for a longer period of time (Dillo et al., 2010). While Burgess et al. (2010) and Banich et al. (2009) saw hypoactivation of various brain regions in the experimental group, the accuracy scores showed no difference, which might potentially signify that compensatory attentional systems aid participants with ADHD. Further the increase in facilitation demonstrated by patients with ADHD in the studies by Banich et al. (2009) and Burgess et al. (2010) could indicate that they weren’t complying with task demands and exerting control (MacLeod, 1991).

A lot of the brain regions found to be under activated by participants with ADHD according to Depue et al. (2010) such as the orbital frontal cortex, the basal ganglia, caudate nucleus, putamen and ventral striatum are involved in rewards processing and of the dopaminergic pathways, which are known to be compromised in ADHD (Carmona et al., 2009). Further the fronto-basal ganglia network is thought to interact with the inferior frontal gyrus as a different mode of inhibition (Aron et al., 2003). Whilst no failure in performance accuracy was noted by Depue et al. (2010), increased response time and inattention was detected. Once again, it is possible that alternate pathways might weigh up for the deficits detected in patients with ADHD, although a general lack of cognitive control was seen.

The hypoactivation of several brain regions observed by Shang et al. (2018) indicates deficits of the frontostriatal network in people with ADHD, which concurs with previous findings that suggest deficits in cognitive control as a result of this (Shen et al., 2020). This matches the accuracy scores where the ADHD group performed worse. Further, Shen et al. (2020) believe that the specific parietal deficits in those with combined type ADHD might underlie differences between inattentive and combined ADHD. Successful inhibitory control has been correlated with the right parietal lobe and right dorsolateral prefrontal cortex (Durston et al., 2002).

Because of the insufficient activity in the pre-supplementary motor area in participants with ADHD, as seen in the study by Mulligan et al. (2011), it is plausible that the networks for response inhibition and selection of response are defective in people with the disorder. Although in spite of functional imaging deficits observed in the inhibition of prepotent motor responses, the behavioral data from the same study does not support these deficits. Neither does Mulligan et al. (2011) observe any other neural activation which might compensate for these deficits.

Societal and ethical considerations

All participants were required to sign informed consent forms in order to participate in these studies. The anonymity and privacy of every participant was protected. However, Schulz et al. (2014) and Mulligan et al. (2011) state that participants were compensated for their participation. Schulz et al. (2014) does not state what participants were compensated. This runs the risk of being ethically concerning as it impacts an individual's willingness to participate and their likelihood of agreeing to something they might have otherwise refrained from.

Limitations

This review has several limitations to consider. To commence, not all articles used the same variation of the Go/No-go and the Stroop task. Because one article used the counting Stroop task and another the face/emotion Go/No-go task, results may vary due to the fact that the tasks themselves measured slightly different things.

While there were no differences in behavioral performance worth remarking, the differences in neural activity exposes alterations in inhibition. Because of the specific experimental setting, one limitation relates to the inability to predict how these differences in inhibitory control would express themselves in day-to-day life for people with ADHD.

The article by Depue et al. (2010) only presented limited information regarding the task results, which meant some results couldn't be compared to that of those in the remaining three articles. Another limitation is the small sample size in a lot of the studies, as well as the fact that two studies relied solely on a demographic of male participants. Most of the studies used an overwhelming majority of male participants and this leads to a less diverse representation of adults with ADHD. As for the inclusion criterions, one limitation is the fact that some of the participants used medication and only abstained from central stimulants the week before the experiment. This is problematic as long term use of central simulants have unforeseen effects and might possibly have caused neural alterations over time in the brains of these participants (Krinzinger et al., 2019).

Lastly, a final limitation is that there were very few studies used in the review. The five Go/No-go studies and four Stroop Task studies present a very limited amount of data, especially considering some of the sample sizes, making the results less generalizable to the broader population.

Final conclusions

Overall there appears to be more convincing evidence in favor of the network perspective of inhibitory control, rather than the modular theory. The interaction of several brain regions appear to impact different aspects of inhibition. Based on the findings from the Go/No-go task, there are no clear cut impairments in motor inhibition for people with ADHD. On the other hand, participants with ADHD did display hyperactivation in other regions such as the thalamus, parietal lobe, occipital gyrus and so on, indicating a probability that alternate systems mediate the inhibitory control responses in adults with ADHD.

To understand the similarities in task performance between the two groups, it could be that once more the participants with ADHD rely on alternate pathways to achieve similar levels of inhibitory control.

Taken together, there appears to be subtle impairments in inhibitory control in adults with ADHD, compared to children with ADHD who have more overt difficulties with inhibition. People living with this disorder might have found alternate ways of coping with these difficulties during certain situations, it is still difficult to anticipate how these neural variances might impact the everyday life of adults with ADHD. To successfully inhibit responses throughout a time limited task, in an experimental setting, is quite different from managing these inhibition impairments within the real world. Additional research would aid in eradicating the gaps regarding the compromised inhibition in adults with ADHD.

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