Role of Reward Systems in ADHD and Impulsive Choice: A Systematic Review

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Student: Alexandra Palombo

Supervisor: Joel Gerafi

Examiner: Oskar MacGregor
Abstract

Attention-deficit/hyperactivity disorder (ADHD) is characterized by hyperactivity, impulsive behavior, and excessive inattention. The diagnosis is divided into different types of ADHD depending on the symptoms. A single cause for the diagnosis has not been found; therefore, various models exist. When choosing between an immediate smaller reward and a later larger reward, ADHD-diagnosed individuals often choose the immediate smaller reward, termed choice impulsivity (CI). Several models have tried to explain this phenomenon. One theory argues that the subjective value of the reward diminishes when the reward is moved further away in time. Others claim that it is a deficit in inhibitory-based executive dysfunction and that ADHD individuals cannot suppress the drive and resist the temptation of the earlier reward. The delay aversion model argues that it is a motivational problem with an abnormality in the reward mechanism making the patients hypersensitive to delayed rewards. The negative affective state that evokes from the delayed rewards makes them want to escape or avoid it and therefore choose the small, immediate reward. The insula and the amygdala mediate both negative and positive emotional processes in the brain and are candidates for this phenomenon. In this systematic review, four scientific studies were selected and included to investigate if the insula and amygdala are the primary CI candidates in ADHD-diagnosed individuals. The systematic review results support the idea that the amygdala correlates with CI in ADHD-diagnosed individuals, therefore supporting the delay aversion model theory of ADHD. A correlation between insula and CI in ADHD-diagnosed individuals could not be established in this systematic review. Understanding the role that emotional structures have in ADHD can help to develop interventions or therapy to cope with the disadvantaged features of ADHD.

Keywords: adhd, choice impulsivity, delay aversion, reward, insula, amygdala
The Role of Reward Systems in ADHD and Impulsive Choice: A Systematic Review

Attention-deficit/hyperactivity disorder (ADHD) is primarily a child and adolescent behavioral condition. The diagnosis is characterized by hyperactivity, impulsive behavior, motor restlessness, and excessive inattention (Tripp & Wickens, 2009). It is usually associated with social and educational disadvantage and is often accompanied by other internalizing (e.g., anxiety) and externalizing (e.g., conduct disorder) comorbid disorders (Sonuga-Barke et al., 2010). ADHD affects up to 5.3% of children and 4.7% of adults worldwide (Kappel et al., 2015). The condition persists into adulthood in 65% of the diagnosed children (Modesto-Lowe et al., 2013). The hyperactivity symptoms decrease over time, but attentional deficits and impulsive behavior maintain (Wender et al., 2001). The diagnostic criteria for ADHD, given by the Diagnostic and Statistical Manual of Mental Disorders (DSM V, American Psychiatric Association, 2013) is divided into two domains; predominantly inattention (poor concentration and organization skills) and predominantly hyperactivity/impulsivity (constant high activity levels, difficulty staying focused on one task and risk-taking). Each domain is described by nine symptoms, of which at least six need to be present to diagnose predominantly inattention or predominantly hyperactivity/impulsivity. If one meets the diagnosis criteria in both domains, one gets diagnosed with a combined type of ADHD. When listing the number of possible combinations for diagnosed ADHD based on the symptoms, 504 combinations become available (Tripp & Wickens, 2009). The availability of different varieties of ADHD shows a potential heterogeneity of the disorder. It might also suggest that a single cause for the diagnosis is unlikely, or a common underlying reason for the disease exist but is expressed in different forms (Tripp & Wickens, 2009). One suggestion is that the diagnosis variability is dependent on which locus of the brain is affected (Sergeant et al., 2003).

When children with ADHD have an option to choose between an immediate smaller reward and a later larger reward, they often choose the immediate smaller reward, termed choice impulsivity (CI) (Sonuga-Barke et al., 1992). Thus, healthy controls can control their
desire for immediate reinforcement and wait for the reward if they have higher-order plans or goals (Plichta et al., 2009).

Rewards are primarily events related to an individual’s survival. They possess a motivational value, e.g., food rewards a hungry individual, and a hungry individual is motivated to look for food. Rewards are generally referred to technically as reinforcers and reinforce stimuli (Ferster & Skinner, 1957). Rewards have three different behavioral functions; (1) Interrupt ongoing behavior and evoke a direct automatic reaction approach without the individual’s active participation, (2) Increase the frequency of a behavior reaction that leads to learning, (3) Function as a goal of voluntary behavior (Schultz, 1997).

In the brain, ventral striatum and the nucleus accumbens (a part of the ventral striatum) process the reward information and are highly interrelated with the neurotransmitter dopamine function. Nucleus accumbens are innervated by mesostriatal dopamine (dopamine primarily mediates feelings of pleasure and reward) and linked to the anterior cingulate cortex, supplementary motor area, insula, and thalamus (Plichta & Scheres, 2014). Dorsal striatum partially processes future rewards. The caudate nucleus (part of the dorsal striatum) is associated with the subjective experience of wanting, craving and desiring (Plichta et al., 2009). The insula and the amygdala mediate emotional processes, both negative and positive, and the anterior region of the insula connects and processes aversive states with the amygdala (Plichta et al., 2009). The insula has an introspective role in one’s conscious perspective of feelings and affective states (Lemiere et al., 2012). These structures are all part of the brain’s reward circuit (Plichta & Scheres, 2014). In healthy controls, the ventral and dorsal striatum in the reward system becomes activated when the individual is subjected to the choice of immediate versus delayed reward.

Several models have different explanations for why individuals with ADHD are more prone to CI than healthy individuals. It is believed that the problem lies within the brain’s reward circuit, but there are different theories on which brain structure is responsible for ADHD individuals’ CI. Some models focus on the subjective value of the reward and how it diminishes when the reward is moved further away in time, termed temporal reinforcement
discounting (Lemiere et al., 2012). According to these models, CI occurs in individuals with ADHD because the larger reward becomes less valuable when postponed in time. They argue for defaulting dopamine signal towards a delayed reward (i.e., the delayed time between the desired response of an individual and the delivery of the reward) or failure of anticipatory dopamine cell firing (Lemiere et al., 2012). Other models describe the CI in ADHD diagnosed individuals as a deficit in inhibitory-based executive dysfunction, making them unable to suppress the drive and resist the temptation of the earlier reward (Lemiere et al., 2012). Within this model, it is believed that the problem lies within the dorsal striatum associated with the subjective experience of wanting, craving, and desiring (Plichta et al., 2009). Both models described above focus on the subjective feeling of pleasure towards quick rewards and that this is the main reason for CI in ADHD individuals. Considerable research has been done during the history of research of ADHD and supports these theories.

Furthermore, “The delay aversion model” that was set out more than a decade ago has a different perspective on CI in ADHD individuals (Sonuga-Barke, 2005). It is argued that it is a motivational problem with an abnormality in the reward mechanism making the patients hypersensitive to delayed rewards (Sonuga-Barke, 2003). When children with diagnosed ADHD cannot prevent or escape delays, they attempt to create non-temporal stimulation by activating themselves with self-stimulating activities or searching for stimulation in their environment. These activities alter the subjective experience of delay and make the wait appear shorter. Hyperactivity and inattentiveness often result from this behavior and drives individuals with ADHD to respond more impulsively towards reinforcements (Sonuga-Barke, 2003). It is believed that the disturbed anticipation of delayed reward in individuals with ADHD makes them choose the immediate small reward to escape the aversive affective state of the delay of the bigger reward (Sonuga-Barke, 2003). According to the delay aversion model, the problem lies within the emotional structures, insula, and amygdala, which processes aversive states (Plichta et al., 2009).

Moreover, a correlation between the severity of the ADHD symptoms and an increased blood flow in the anterior region of the insula and the amygdala has been found in
ADHD-diagnosed individuals (Plichta et al., 2009). However, other studies have shown that ADHD-diagnosed children show more motivation by reducing the delay time than higher the reward, compared with healthy controls (Modesto-Lowe et al., 2013), arguing that it is not the reward that is the driving source for the choice, rather the delay itself. Thus, there is broad support for delay aversion in ADHD from behavioral studies, but it has not been researched as much as other theories (Van Dessel et al., 2018).

Functional magnetic resonance imaging (fMRI) is a brain imaging method commonly used to visualize brain activity in different regions by measuring the blood oxygen level-dependent (BOLD) effect. Increased blood flow occurs when a brain region becomes activated, the fMRI can indirectly measure neural activity by measuring changes in the blood flow (Gazzaniga et al., 2014). Decision-making and reward/non-reward tasks are designed to measure neural function activity during reward anticipation and delayed reward. The tasks are combined with fMRI to better understand reward-related neural function activity in particular brain structures (Dubol et al., 2018). By looking at fMRI studies combined with reward/non-reward or decision-making tasks, neural activation can determine the most plausible difference in CI between the two groups. For example, an aversive perception of delayed rewards should reflect increased activation of primary emotional structures such as the insula and amygdala.

So, does the negative emotional effect of unavoidable delay drive the preference for CI in ADHD-diagnosed individuals? This article aims to systematically review the current scientific findings of the delay aversion model theory that the insula and amygdala are the primary candidates for CI in ADHD-diagnosed individuals by investigating how aversion to delay affects these individuals. In addition, this review will include articles that have been using fMRI in combination with reward/non-reward or decision-making tasks on ADHD-diagnosed individuals.

The hypothesis is that there will be group differences in the neural responses of the insula and amygdala during delayed rewards.
By understanding the mechanism behind the role of the reward system in individuals with ADHD and investigating alternative models, we might provide the correct tools to ADHD diagnosed individuals to sustain motivation, be less impulsive, and be more attentive to their behavior. In addition, these tools could generate future success for individuals with ADHD in areas that demand higher cognitive abilities. Finally, as mentioned earlier, a single cause for the diagnosis is unlikely; therefore, investigating multiple models should be beneficial in this research area.

Method

Search Strategy

The author searched for the scientific papers from PubMed (PM) and Web of Science (WS) on the 4th of March, 2021. The initial search started with a trial of different keywords to find the most effective key-string possible, resulting in hits of relevant research articles for the chosen subject. The final chosen key-string was: “(Attention deficit hyperactivity disorder or ADHD or Attention deficit disorder or ADD) and reward and delay aversion and (brain OR neuroscience OR insula OR amygdala)” which resulted in a total of $n=49$, $n=21$ (PM), and $n=28$ (WS). The keywords needed to be present in the title or the paper’s abstract to be included in the literature search. The search was limited to peer-reviewed research articles in English, free of charge, and published between 1990-2021. The search was restricted to the time period from 1990 to the present because no fMRI studies were published before this year. The articles were saved and imported into the software tool EndNote for screening after duplicates, $n=13$ duplicates were removed, and the remaining $n=36$ research articles were further screened (see the following section). A complete illustration of the literature search process is shown in Figure 1.

Inclusion & Exclusion Criteria

After screening the title and abstract of $n=36$ articles, an exclusion of $n=28$ was made. The title and abstract did not reach the inclusion criteria (review articles, animal research, not included fMRI studies, participants were not in line with the criteria). A total of
n=8 were downloaded and saved on a computer where the author read the full text. After full-text reading, a total of n=4 were excluded due to the wrong type of intervention. Thus, a total of n=4 met the criteria and formed the basis of this systematic review (Figure 1). The inclusion criteria for the systematic review were as follows, (1) females and male children, adolescents and adults participants with clinical or self-reported ADHD, (2) a control group consisting of typical healthy individuals without ADHD, (3) fMRI scan combined with reward/non-reward tasks or decision-making tasks. The systematic review’s exclusion criteria were as follows, (1) review articles or theoretical articles, (2) animal studies, (3) studies not directly related to neural correlations of delay aversion, CI, reward, insula, amygdala, or ADHD, (4) fMRI scan combined with other intervention than reward/non-reward or decision-making.

**Data Extraction**

The data extracted from the included articles are as follows: the number of participants in the groups, age, gender, domains of ADHD, intervention (reward/non-reward or decision-making task), the BOLD signal of the insula, and amygdala during delayed reward between ADHD-diagnosed individuals and healthy controls.
**Figure 1**

PRISMA 2009 Flow Diagram

Results

Based on the PRISMA search, four studies were selected and included in this systematic review (shown in table 1) to investigate the delay aversion theory by looking at insula and amygdala as the primary candidates for CI in ADHD-diagnosed individuals. The selected studies differ in several aspects, such as tasks and the activity of different brain structures. In addition, the task selection was based on which type of outcome was investigated in the study (shown in table 1).

Reward/Non-reward Task

Lemiere et al. (2012) used the Escape delay incentive task and fMRI to measure the BOLD response of non-escape delay and escape delay in the amygdala and insula of adolescents with ADHD (see table 1). During the Escape delay incentive task, the $N=20$ participants were presented with either a square-shape cue (conditional delay) or a circle-shape cue (non-escape delay) followed by an anticipation delay (3-3.5 s). When a white square target appeared after the anticipation delay, the participant responded by pressing a button as quickly as possible. During the conditional delay, the reward or non-reward depended on how quickly the participant pressed the button. During the non-escape delay, the participants could not escape the delay no matter how fast they responded. A sign of reward or non-reward was presented for 3 seconds, followed by a reward (no delay) or non-reward (delay 8-17 seconds). The ADHD group showed hyperactivation in the bilateral insula and the amygdala during the non-escape delay but not the control group. No significant difference between groups in neural activation during the condition of escape delay was found.

The Van Dessel et al. (2018) study also used the Escape delay incentive task together with fMRI to measure the BOLD response in the amygdala and insula during the non-escape delay and escape delay (see Table 1). The $N=61$ participants were presented with one of three different cues; triangle (conditional delay), circle (certain delay), or diamond (no delay), followed by an anticipation delay (3-3.5 seconds). When a white square target appeared after the anticipation delay, the participant responded by pressing a button as quickly as possible.
The reward or non-reward depended on how quickly the participant pressed the button during the conditional delay trial. No matter how fast they responded, the participants could not escape the delay during the non-escape trial. During a no-delay trial, no delay followed. The sign of reward or non-reward was presented for 3 seconds, followed by the reward (no delay) or non-reward (delay 2-14 seconds). During the non-escape delay, the ADHD group showed increased activation in the bilateral insula and amygdala compared to the control group. There was no significant difference between the groups in neural activation during the escape delay in either escape delay condition.

**Decision-making task**

Plichta et al. (2009) used the Validated intertemporal choice paradigm and fMRI to measure the BOLD response of immediate rewards and delayed rewards in the insula and amygdalas between the ADHD group and controls (see Table 1). $N=26$ participants needed to choose between two monetary rewards that differed in amount and delay delivery. If selecting the smaller reward, a shorter time to receive the reward followed (today, two weeks, or four weeks). Choosing the larger reward (1%-50% higher than the smaller one), a longer delay of receiving the reward followed (two or four weeks later than the shorter option). There was no time limit for the participants to make the decision. Higher bilateral neural activation in the amygdala was shown in the ADHD group during delayed reward and decreased neural activation in healthy controls. Also, neural activity toward delayed rewards significantly correlated with symptom severity. However, there were no significant differences in insula activation between the groups (Plichta et al., 2009).

In the Mies et al. (2018) study, the Delay discounting task was used together with fMRI to measure the BOLD response of the amygdala and insula during delayed reward between the two groups (see Table 1). In the delay discounting test, $N=46$ participants chose between a small immediate reward (2-8 cents after 1.5 seconds) or a large fixed delayed reward (10 cents after 5-25 seconds). Participants were not informed of the exact delay duration of the large reward before choosing. In addition, a control condition was made where the participant had to select the larger reward over the smaller one. Finally,
participants were asked to scale the subjective experience of waiting (negative to positive) post scanning. During the delayed reward, increased activation in the amygdala was found in the ADHD group. However, there were no significant differences in insula activation between the groups during delay conditions. In addition, group differences could be established in the subjective experience of waiting. A correlation between the negative subjective experience of waiting and increased neural activation in the amygdala in the ADHD group was found (Mies et al., 2018).
### Table 1
*Articles included in the systematic literature review*

<table>
<thead>
<tr>
<th>Author</th>
<th>Participant</th>
<th>Task</th>
<th>Comparison</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemiere et al.</td>
<td>ADHD (combined)</td>
<td>Reward and non-reward task</td>
<td>Healthy age and gender-matched controls</td>
<td>Bilateral Amygdala: Increased neural activity</td>
</tr>
<tr>
<td></td>
<td>(n=10)</td>
<td>(Escape delay incentive-task)</td>
<td>(n=10)</td>
<td>Bilateral Insula: Increased neural activity</td>
</tr>
<tr>
<td></td>
<td>mean age: 14.72</td>
<td></td>
<td>mean age: 14.4, SD: 1.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD: 1.49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Dessel et al.</td>
<td>ADHD (combined)</td>
<td>Reward and non-reward task</td>
<td>Healthy age and gender-matched controls</td>
<td>Bilateral Amygdala: Increased neural activity</td>
</tr>
<tr>
<td>(2018)</td>
<td>(n=29)</td>
<td>(Escape delay incentive-task)</td>
<td>(n=32)</td>
<td>Insula: Increased neural activity</td>
</tr>
<tr>
<td></td>
<td>mean age: 14.51</td>
<td></td>
<td>mean age: 14.74, SD: 2.10</td>
<td></td>
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<tr>
<td></td>
<td>SD: 2.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plichta et al.</td>
<td>ADHD (combined)</td>
<td>Decision-making task</td>
<td>Healthy age, IQ, and gender-matched controls</td>
<td>Bilateral Amygdala: Increased neural activity</td>
</tr>
<tr>
<td>(2009)</td>
<td>(n=14)</td>
<td>(Validated intertemporal choice paradigm)</td>
<td>(n=12)</td>
<td>Insula: Not significantly different from control</td>
</tr>
<tr>
<td></td>
<td>mean age: 23.3</td>
<td></td>
<td>mean age: 23.6, SD: 1.9</td>
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<tr>
<td></td>
<td>SD: 5.2</td>
<td></td>
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</tr>
<tr>
<td>Mies et al.</td>
<td>ADHD (combined)</td>
<td>Decision-making task</td>
<td>Healthy age and gender-matched controls</td>
<td>Amygdala: Increased neural activity</td>
</tr>
<tr>
<td>(2018)</td>
<td>(n=21)</td>
<td>(Delay discounting-task)</td>
<td>(n=25)</td>
<td>Insula: Not significantly different from control</td>
</tr>
<tr>
<td></td>
<td>mean age: 15.1</td>
<td></td>
<td>mean age: 15.4, SD: 1.7</td>
<td></td>
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<tr>
<td></td>
<td>SD: 1.8</td>
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</table>

*Note.* Summary of all studies accounted for in this review, showing the use of methodology, data of patients and healthy controls, and the study’s outcome. \(n\)= number of individuals; SD=standard deviation.
Discussion

The delay aversion theory of ADHD proposes that the preference for CI in ADHD-diagnosed individuals is to escape or avoid the aversive negative effect they experience during delay reward (Sonuga-Barke, 2003). Based on the literature on neural correlates of the processing of aversive stimuli, the amygdala and insula seem to be the prime candidates for the aversive state and CI in ADHD-diagnosed individuals. Therefore, this article aimed to investigate whether aversion to delay in ADHD-diagnosed individuals correlates with increased/decreased neural activation in the insula and amygdala by using fMRI combined with reward/non-reward or decision-making tasks. In addition, a result of a group difference in the neural responses of the insula and amygdala during delayed rewards was hypothesized.

The results based on the included studies are partially conflicting (see table 1). Numerous studies support the idea that increased neural activation in the amygdala correlates with delayed reward in ADHD-diagnosed individuals. However, increased neural activation in the insula during delayed reward was found in reward/non-reward tasks studies but not in the decision-making tasks studies; therefore, an association between increased activation in the insula and delayed reward could not be established.

All four studies showed hyperactivation in the amygdala within the ADHD group during delayed reward (Lemiere et al., 2012; Mies et al. 2018; Plichta et al., 2009; Van Dessel et al., 2018). More specifically, Plichta et al. and Lemiere et al. found decreased amygdala activation during delayed reward in the control group compared to the ADHD group. Also, in the Mies et al. 2018 study, a correlation between the negative subjective experience of waiting and increased neural activation in the amygdala was found. This finding supports the delay aversion theory that there are group differences in the neural activation in the amygdala during delayed reward.

In the studies of Lemiere and Van Dessel, where the reward/non-reward tasks were used, the insula showed increased neural activation during delayed reward in the ADHD group. Both studies included reward/non-reward tasks; the delayed reward outcome was not
under the participant’s control. During the experiment, the brain structures’ neural activation did not fully differentiate between the cues that had a certainty outcome and an uncertain outcome. That particular reaction could have been conditioned to specific cues instead of the delayed related features during the procedure. However, in the Plichta et al. (2009) and Mies et al. (2018) studies, no correlation between hyperactivation of the insula and delayed reward could be found. Plichta et al. (2009) showed that the immediate reward was delivered after the experiment and could also be experienced as a delayed reward. As a result, a reduced CI in the ADHD group might have occurred. The studies of Lemiere et al. (2012) and Van Dessel et al. (2018) used the reward/non-reward tasks where the delayed reward outcome was not under the participant’s control, while Plichta et al. (2009) and Mies et al. (2018) used decision-making tasks, where the temporal choice was under the participant’s control during the experiment. The different results could indicate more activation in the insula during forced delay than during individual choice of delayed reward. No control of an outcome might generate the non-escape delay’s aversive aspect rather than the delay itself. The insula correlates with the awareness of emotional feelings and the body’s reaction to those feelings, such as heartbeat and pain (Lemiere et al., 2012). By having control over an outcome, the response of one’s body might not be as strong as in the state of not having control; therefore, a lower neural activation in the insula might appear during decision-making delayed rewards than non-escape rewards. This theory aligns with the group differences of the subjective experience of waiting in the Mies et al. (2018) study. Also, Mies et al. (2018) was the only study that used a post-experiment self-report to measure the participant’s subjective feeling during the delayed reward. The insula and the amygdala mediate emotional processes, both negative and positive (Plichta et al., 2009). Comparing the self-report result with the neural activation in the insula and amygdala in each case could benefit the research of establishing a correlation between an aversive affective state of delayed reward and increased neural activation in the insula and amygdala.

In Plichta et al. (2009), the participants were adults, whereas, in Lemiere et al., 2012; Mies et al., 2018; Van Dessel et al., 2018, experiments were performed on adolescent
participants (see table 1). These group differences might have affected the results since the ADHD disorder has symptoms that decrease over time, thereby explaining why Plichta et al. (2009) did not report a correlation between the insula and delayed reward in the ADHD group. Also, the number of participants in all studies was relatively low (see table 1), especially in Lemiere et al. (2012) and Plichta et al. (2009), which affects the statistical outcome in the results.

Group differences in IQ occurred in Mies et al. (2018), Lemiere et al. (2012), and Van Dessel et al. (2018) (Mies et al., 2018, ADHD group mean=98, healthy group mean=106, Lemiere et al., 2012 ADHD group mean=96.3, healthy group mean=116.5, and Van Dessel et al., 2018 ADHD group mean=99.5, healthy group mean=111.6). The participants in Plichta et al. (2009) had matched IQ between the groups (ADHD group mean=108.5 and healthy group mean=112.3). There is a possibility that the results partially conflicted because of this reason. A lower IQ could indicate individual difficulties with higher-order plans or goals and, therefore, problems during delayed rewards. The correlation between the insula and delayed reward in Lemiere et al. (2012) and Van Dessel et al. (2018) could have been affected by the individual’s IQ rather than the ADHD diagnosis.

The participants’ use of psychostimulant medication was limited before the experiment in all four studies. Although, the time limit for the detoxing and the dose varied between the studies. In Plichta et al. (2009), seven participants detoxed six weeks before the experiment, and seven participants detoxed four days before the experiment. In Lemiere et al., 2012; Mies et al., 2018; Van Dessel et al., 2018, detoxing was made 72-24h previous to the experiment. Therefore, the amount of time for the participants to detox and the medication dose could impact the results. Also, Lemiere et al. (2012) did not exclude participants with mood or anxiety disorders, which could affect the result.

The quality of the studies could somehow be determined by which journal they have been published, and therefore one tends to rely more on the studies published in high-impact journals. For example, Plichta et al. (2009) were published in Biological Psychiatry, IF=12.095. In contrast, Lemiere et al. (2012) was a pilot study and published in Brain

Limitations

The systematic review included a small size of studies; a total of four studies resulted from the search in line with PRISMA guidelines. Therefore, a small sample size of articles could have affected the results. Furthermore, the author selected all articles included in this paper and had no second opinion or expertise help; therefore, a biased view could have affected the choice of articles.

Looking at other brain structures involved in the reward system, such as ventral and dorsal striatum, or measured neural activation during other temporal reward differences, such as reward anticipation or reward delivery, could have given this review a broader perspective to answer the scientific question and to compare the theories of the different models with each other.

The number of participants was relatively low in all studies. A larger sample could have given more significant data. In addition, the age differences between the participants in the studies occurred. By including more studies on adult participants, an alternative pattern could have been discovered. All four studies used participants with the combined type of ADHD. An experiment with domain group differences might have provided us with eventual specific diagnose characteristics correlated with the neural activation of the brain structures of interest during delayed rewards.

Societal and ethical aspects of enquiry

All studies included in this systematic review were performed with ethical permission and designed in a way that did not harm the people that were involved in the study, neither physically nor mentally.

This systematic review indicates a progression towards a broader understanding of the neural correlates involved in diagnosing ADHD. By being a common diagnosis of the population with social and educational disadvantages, primarily associated with criminality,
drug abuse, unemployment, and violence (Erskine et al., 2016), most result in a significant impact on the society and the society’s economy. Focusing research on interventions that could help sustain motivation, be less impulsive, and be more attentive to the behavior of the ADHD diagnosed individuals might help to higher the education for these individuals, which might lead to success in areas that demand higher cognitive abilities. Having higher education can be an advantage to a more manageable lifestyle and positively impact society’s economy. Because of multiple varieties of ADHD, a single cause for the diagnosis is unlikely; therefore, more research needs to be done on alternative models of ADHD. By understanding the main reason for the diagnosis’s characteristics, we might find interventions or therapy that helps to cope with the disadvantaged features of ADHD and, in some cases, even substitute medication. Medication might not be the best alternative in all matters of ADHD, and some individuals might benefit from therapy and intervention. Also, research on interventions or other strategies that can help with arousal regulation should be developed and provided to parents, teachers, or other individuals who are part of this individual’s education. More research could be advantageous for society and hopefully decrease crime, drug abuse, and criminality.

**Conclusion**

This article systematically reviewed the current scientific findings of the delay aversion model theory that the insula and amygdala are the primary candidates for CI in ADHD-diagnosed individuals by investigating how aversion to delay affects these individuals. The findings from this systematic review suggest that the amygdala correlates with CI in ADHD-diagnosed individuals. Correlation between the insula and delayed reward could be found in individuals with ADHD during the reward/non-reward tasks studies but not in the decision-making tasks studies. The systematic review could not fully establish that the increased activation in the amygdala was due to subjective negative feelings of delayed reward. Nevertheless, this systematic review supports the central concept of the delayed aversion model that the primary candidate for CI in ADHD diagnosed individuals is the amygdala. Thus, this systematic review partly supports the idea that the primary candidate
for CI in ADHD individuals is the insula and that the subjective aversive feeling of delayed reward is the reason for CI in ADHD diagnosed individuals. The support of the delayed aversive model does not necessarily dismiss well-researched theories that support the idea of the reward itself as the main reason for CI in ADHD individuals. Instead, it shows that multiple explanations for this phenomenon exist and that research needs to investigate further in this area to understand ADHD and the differences in the diagnosis. This review has only researched the neural activation of the insula and amygdala during delayed reward. Studying other brain structures involved in the reward system, other temporal differences of reward, and different domains of ADHD might give us a broader understanding of the ADHD diagnosis. Also, further research could help to establish a link between different domains of ADHD and different CI models that could help explain the phenomenon. More research needs to be done to understand ADHD better, especially research in the impulsiveness of individuals with ADHD.
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