

Altered Time Perception in Attention Deficit Hyperactivity Disorder (ADHD)

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Abstract: Attention-Deficit/Hyperactivity Disorder (ADHD) is a common neurodevelopmental disorder characterized not only by inattention, hyperactivity, and impulsivity, but also by pronounced impairments in time perception and temporal processing. Increasing evidence suggests that deficits in time estimation, reproduction, and temporal control play a critical role in the everyday functional difficulties experienced by individuals with ADHD. This review aims to synthesize current findings on the cognitive, behavioral, and neurobiological mechanisms underlying altered time perception in ADHD. Drawing on evidence from behavioral experiments, neuroimaging studies, pharmacological research, and non-pharmacological interventions, this paper examines how dysfunctions in fronto-striatal circuits, cerebellar systems, and large-scale brain networks contribute to temporal processing abnormalities. In addition, the effects of stimulant and non-stimulant medications, as well as emerging interventions such as cognitive training and neurofeedback, are reviewed with respect to their influence on time perception. Understanding time perception deficits in ADHD provides important insights into the disorder's core mechanisms and offers promising directions for targeted assessment and intervention strategies.

Keywords: Attention-deficit/hyperactivity Disorder, Time Perception, Executive Function, Neuroimaging, Cognitive Training.

1. Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a prevalent neurodevelopment disorder, with observable symptoms of inattention, hyperactivity, and impulsivity that persist from early life onward [1]. Both children and adults suffer from it and generally present challenges with learning, organization, and time management. In addition to the classic challenge with attention and executive processing, it has recently emerged that more evidence shows individuals with ADHD also have disorders with time perception, which impair their capacity for time estimations, tracking, and processing. Such time processing disorders in ADHD could partially explain why they have issues with waiting, carrying out tasks in time, and eventually with completion [2-3].

Time awareness is the basis for human cognition in general. It enables a person to predict events, control their behavior, and respond appropriately to the requirements of the environment [4]. Damage to time processing has been linked to affected performance, control over emotions, and interpersonal relations in individuals with ADHD. Knowledge of time perception mechanisms in ADHD is essential for adopting strategies that make day-to-day life easier for these individuals.

Neuroscientific research has linked impaired time sense in ADHD with fronto-striatal and cerebellar dysfunction, as well as atypical communication between large-scale brain networks such as the Default Mode Network (DMN) and Central Executive Network (CEN) [5-6]. These networks that enable attention, working memory, and behavioral control are thought to underlie variability and instability of timing that is characteristically observed in ADHD.

Behavioral and neuroimaging studies have all consistently reported increased reaction time variability, impaired duration judgments, and decreased synchronization with

external rhythm in ADHD [7-8]. These processes are partially normalizable by pharmacological therapy with stimulant medication through dopaminergic and noradrenergic modulation [9-10], but do not completely reverse temporal deficits. There has been evidence in recent years for non-pharmacological interventions like cognitive training, neurofeedback, and game-based brain training to improve timing accuracy and attentional control [11-12].

This review is aimed at providing an overview of the current understanding of cognitive and neural mechanisms of time-perception impairments in ADHD. It integrates evidence from cognitive, behavioral, and neuroimaging studies, pharmacological and non-pharmacological interventions. By integrating information from different perspectives, an attempt is made in this review to understand the role of time-processing weakness in the onset of ADHD symptoms and review time-based treatments for enhancing cognitive-behavioral functioning.

2. Neurobiological Bases for Time Perception in ADHD

Time processing in the human brain with ADHD is also a complex phenomenon in which multiple regions, chemicals, and systems in the brain work in a complex manner with each other. Time perception deficiencies in individuals with ADHD cause difficulties for these individuals in understanding time intervals in an appropriate manner in relation to the timing of events in the future. Time perception deficiencies in ADHD patients can also be demonstrated in their poor time management skills in the sense that these individuals become late, logically since they do not have any way to understand time in an appropriate manner [13].

At the level of the brain network, the Default Mode Network (DMN), engaged during rest and daydreaming, is also involved in time processing. In ADHD, the DMN

exhibits poor task-related deactivation, leading to persisting distractibility and inability to maintain attention [14]. Conversely, the Task-Positive Network (TPN), consisting of the dorsal attention network and the central executive network, is concerned with the maintenance of attention and cognitive control. Normally, it is assumed to function in an antagonistic manner with regard to the DMN, where the latter is supposed to be deactivated during goal-related activities [15]. Nevertheless, dysfunctional activation in the central executive network (CEN), for instance, reduced activation in the dorsolateral prefrontal cortex, could upset the active processing for temporal information in the ADHD brains leading to time-related bias [16]. Additionally, dysfunctional regulation in the salience network (SN) could impair the healthy inter-network dynamics between the DMN-TPN [17], further contributing to time-related perceptual instabilities. Therefore, attention is likely to wander more, thus impairing the efficient temporal information processing in the brain system. As shown in Figure 1, time perception impairments in ADHD are associated with dysfunctions across multiple levels, including brain structure, large-scale neural networks, neurotransmitter systems, and behavioral regulation.

Neuro-anatomically, people with ADHD show reduced activity in their prefrontal cortices, making it difficult for

these individuals to gauge the duration of activities or events. Secondly, reduced sensitivity in the striatum region not only impairs the individual's internal clock duration but also their reward duration, making it challenging for these individuals to perform activities that require their attention for time duration [18]. Additionally, dysfunctional regions in the cerebellum cause an impairment in the "internal clock," making it difficult for these individuals to gauge time in their daily lives [19].

Neurotranschemically, dopamine levels and other noradrenergic systems also have a pivotal role in the control of attention, incentive motivational systems, and time processing in the human brain. The function in the ADHD syndrome is either impaired in dopamine/norepinephrine systems or is imbalanced, with the principal areas being the medial Prefrontal cortex region/striatum [20]. Dopamine, which is responsible for the reward-related execution of tasks, its deficiency in the brain translates to reduced individual ability to maintain attention and motivation over time, hence hampering time processing. Similarly, norepinephrine, which regulates attention and alertness, is essential for maintaining focus. Reduced norepinephrine levels also compromise the brain's ability to accurately track time, making it challenging to process both short-term and long-term durations [21].

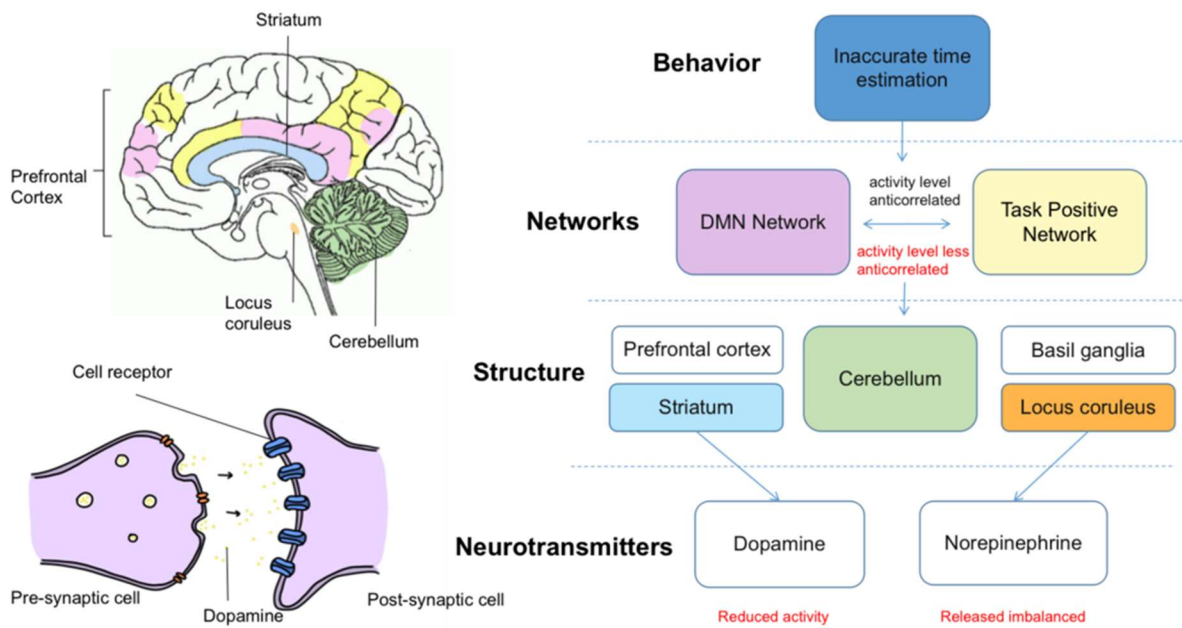


Figure 1. Schematic diagram of the neural mechanism underlying time processing in ADHD.

This diagram presents the neurobiological pathways of time perception in ADHD patients and the differences between them and normal function from the perspectives of structure, network, neurotransmitters, and behavior. Key brain regions that functions while an individual process time are annotated. Dopamine is one of the main dysfunction neurotransmitter which are associated with the core behavioral manifestation of "poor time estimation"; Color coding corresponds the labeling of left brain regions (shaded areas) with right structures and networks, with red text highlighting ADHD related activity abnormalities compared to normal neural processes.

3. Neuroimaging Research on Time Perception in ADHD

Temporal information processing is a complex cognitive function involving multiple stages and numerous brain regions, including the basal ganglia, prefrontal cortex, and their associated neurotransmitter systems. Research has shown that these neural structures each regulate specific components of timing, and their relative importance varies depending on the demands of a given temporal task.

(1) Cerebellum

Functioning in the posterior inferior area of the brain, the cerebellum is also intimately involved in time perception aside from its functions in motor activities. It is also heavily involved in cognitive tasks, particularly in those associated with time processing [22]. In a subject with ADHD, the

disruption in the cerebellum is directly associated with time perception difficulties in that subject. Neuroimaging research illustrates that there is reduced activation within the cerebellum during time-estimation tasks and time sequences for an ADHD subject, which is associated with their inaccurate responses and poor fluency in time-related tasks [23].

The cerebellum has key roles in predicting the time consequences of behavior, helping an individual time their actions in a correct manner. For example, in motor timing tasks, the cerebellum is responsible for the calculation of the correct timing for an action that is critical in motor timing. However, it appears that timing is affected in ADHD, resulting in poor behavioral strategies in daily life situations characterized by inappropriate responses in relation to time [24].

Also, research done by Noreika et al. asserts that there is a possible link between the presence of function-related impairments in the cerebellum with impulsivity control difficulties, in addition to emotion regulation, in ADHD. Function-related impairments in the cerebellum in these domains could possibly affect impulsivity levels in time-pressured situations in individuals with ADHD.

(2) Basal Ganglia

The basal ganglia, a set of subcortical nuclei whose main function is closely associated with motor control/habits, also participate in time perception in their own right. Individuals with ADHD have dysfunctional regions within their basal ganglia, which immediately affects their time perception performance [25]. The basal ganglia have also been proposed to represent an "internal clock," making contributions in regions associated with the performance of time intervals in order to control responses in time-related tasks.

Among the studies that were found is the meta-analysis done on suprasecond motor timing in fMRI studies by Wiener et al. [26], where the meta-analysis focused on the differences in activities in the brain for specific timing tasks between those with ADHD and those with normal cognitive abilities. The study found that those with ADHD exhibited reduced activities in the basal ganglia area, more specifically in the striatum, and in the cerebellum compared to those with normal cognitive abilities. Lower activities in these regions were linked with higher levels of error in time-related tasks [27].

Additionally, the dysfunction in the basal ganglia associated with ADHD could also relate to other areas, such as attention and perceptual skills, rather than just motor control. According to Toplak et al., for instance, any disruption in the connectivity between the basal ganglia and the prefrontal cortex could also impair the entire time perception function in a person with ADHD. All these could lead to the difficulty associated with time-based tasks experienced by these individuals.

(3) Prefrontal Cortex

The prefrontal cortex is a major region where these functions (executive function/self-regulation) affect time perception in ADHD. There is also reduced activation in the area in ADHD patients, especially in those tasks that involve prospective timing and delayed choice [28]. Studies show that the prefrontal cortex is an essential region in the evaluation, selection, and storage of time-related information, with poor performance in these tasks associated with its dysfunction in ADHD. Dysfunction in the prefrontal cortex is also closely linked with impulsivity and inattention in ADHD.

The patients show excessive impulsivity, even with time constraints, because the prefrontal cortex is associated with self-regulation control. At the same time, it has been found that the activation level in the prefrontal cortex is significantly correlated with time perception capabilities in ADHD (Hart et al., 2012). There is also a negative linkage between time perception performance and the level of activation in the prefrontal cortex, indicating that the dysfunction in the prefrontal cortex is possibly an underlying cause for time perception difficulties in ADHD patients.

4. Studies of Time Perception by Cognition and Behavior for ADHD

Research has ever revealed that ADHD individuals exhibit vigorous cognitive bias in the experience of time. Excessive variability of reaction is the most common pattern, reflecting difficulties in having regular distribution of attention and cognitive control for temporal activities [29]. At the same time, they overestimate brief intervals and underestimate larger ones [30], and such non-linear time estimation indicates an imbalance proportionate to their internal clock mechanism. The general deficit in time perception in ADHD, thus, is not simply a fundamental timing problem, but also reflects more widespread impairments in working memory, maintenance of sustained attention, as well as self-monitoring functions.

When looking at it from the level of specificity for the tasks, multiple time processing tasks identify multi-dimensional cognitive impairments in individuals with ADHD. From time estimations, it is found that their judgments on time show an increasingly unstable pattern, with a possible bias towards the actual time duration, reflecting the combined effect of inattention and interference with internal clock rate modulation [31]. In time production tasks, the initiation for their timing responses is early or late in individuals with ADHD, indicating inabilities in relating progress with self-control. Time reproduction tasks were employed on these individuals, where it showed that their time intervals significant to the target time durations were shorter in length with reduced regularity, indicating a deficiency in precision, accuracy, and representativeness within internal time. Time-keeping tasks involving finger tapping also identify deficiencies in the manner they attempt rhythm synchronization and prediction for individuals with ADHD, who also appear completely incapable of internal rhythm pattern formation following temporal information processing, indicating that they have structural instabilities in time processing capabilities, inabilities in predicting, estimating, or sustaining time durations/intervals.

Outside the objective experimental tasks, it is also significant to explore time perspectives from a subjective viewpoint, where it would help in understanding the nature of time processing in individuals with ADHD more effectively. Studies done using the Zimbardo Time Perspective Inventory (ZTPI) showed adults with ADHD had stronger "present-hedonistic" and "past-negative" time perspectives, with poor future-oriented planning (Ptacek et al., 2019). Their time perspective is distorted in a manner where they opt for immediate rewards in terms of present pleasure but are incapable of making an extended effort for any "future objectives." Again, it is apt to say that their time processing capacity points toward their deficiency in "psychological time extension." That is, they lack in deferred gratification

and long-term planning capabilities because they do not have adequate "psychological time extension".

Time perception weakness is also visible within daily activities. Individuals with ADHD have difficulty appropriately gauging the time required for the execution of a task, with an inclination toward low estimates for either preparation time or execution time, thus perpetually acting in a state of procrastination and lateness for deadlines. Time blindness, characterized by an internality diminished intuitive sense for time passage and inaccurate adjustments within behavioral cycles, is commonly anticipated within their observation for their own periods for these action cycles to continue. The latent cognitive problem for these behavioral complaints is associated with the poor regulation within the cognitive control mechanisms for time monitoring functions, with an overfiled need from external stimuli yet loss of continuous time monitoring for time-based tasks simultaneously. Adding its propensity, it also perpetuates classic tendencies within ill-organized planning strategies, impulsive choice, and inability within daily entrainment cycles. Barkley et al. [14] stated vigorously the direct relevance between these mentioned behavioral complications with the core cognitive processes underlying ADHD and excessive living on immediate gain reward systems in addition to their poor monitoring for long-term objectives.

Behavioral intervention is an important tool for improving time processing and executive function in ADHD. Time Management Training compensates for internal time monitoring failures through the implementation of external temporal structures, the setting of explicit task routines, and the provision of immediate feedback concerning execution performance. In addition, cognitive-behavioral therapy (CBT) has proven a dramatic impact on the correction of time-related behaviors. Procrastination and impulsive decision-making are diminished by teaching individuals the technique of delayed gratification, increasing self-monitoring ability, and restructuring the subjective experience of time passage.

5. Pharmacological Interventions

Pharmacological treatment is the most common and effective ADHD treatment, and also provides valuable information about the neural process of time perception impairments. Time processing relies on the modulation of dopamine and noradrenaline activity in basal ganglia and prefrontal cortex. Drugs that target these neurotransmitters can therefore not only induce remission from clinical signs but also modulate temporal cognition.

The most common of the ADHD pharmacotherapies are stimulant drugs. The most common drugs used are methylphenidate (MPH) and dextroamphetamine. These drugs act primarily by increasing the levels of necessary neurotransmitters, like norepinephrine in the brain, thus enhancing concentration and reducing impulsive behavior. Various studies have demonstrated low dopamine levels in the striatum and prefrontal cortex of individuals with ADHD, thus vindicating that medication will offset this deficiency. For instance, Campey et al. tested 35 children aged 7-12 years with ADHD taking osmotic controlled-release methylphenidate (OROS-MPH) under working memory and impulse control tests. Evident was the increased ability in their working memory, along with more patience in choosing delayed reward over the placebo group, and less preference for small immediate rewards. This would indicate that

medication reduced their impulsivity to a great extent. The study's effect size was moderate (Cohen's $d \approx 0.5$), which supports the robustness of the findings. With respect to time perception, evidence is complex. While much research has been unable to report significant improvement, there were findings by Smith et al. that the percentage of time discrimination error in ADHD boys dropped from 40.5% with placebo to 32.5% following methylphenidate administration, showing that stimulants are able to have some impact on the processing of time in ADHD.

Non-stimulants are another category of medication, and atomoxetine is the most prevalent among them. Unlike stimulants, the main effect of atomoxetine is to increase levels of norepinephrine in the prefrontal cortex (Bymaster et al., 2002). Since reuptake of dopamine in the prefrontal cortex is partly mediated by norepinephrine transporters, atomoxetine also increases dopamine signaling indirectly. Through this mechanism, it increases attention and reduces impulsivity in ADHD patients without inducing strong stimulatory effects. In clinical daily practice, atomoxetine generally produces its effects between 2 to 4 weeks, much later than with the use of stimulants (Kratochvil et al., 2006). Some studies have shown that children treated with atomoxetine perform better on tests of sustained attention and have improved impulse control compared to children on placebo. Although its effect size is generally smaller than that of stimulants (Cohen's $d \approx 0.3-0.5$), its therapeutic effects are long-term reliable and involve zero risk of addiction. Few findings exist of its direct effect on the perception of time. Nevertheless, research indicates that atomoxetine increases the reverse correlation between the default mode network (DMN) and the task-positive network (TPN), indirectly enhancing cognitive control in ADHD. This means that atomoxetine can improve time processing ability by facilitating attention and working memory. As regards side effects, atomoxetine is well tolerated and most frequently associated with mild loss of appetite in some 15-20% of patients, drowsiness in some 10%, or with small increases in blood pressure. It has no risk of addiction compared to stimulants and is also very suitable for those patients with comorbid tic disorders or anxiety disorders since the latter can be worsened by stimulants. Thus, atomoxetine is often used as a stimulant medication alternative in clinical practice.

6. Training and Neurofeedback of time processing deficits in ADHD

Besides pharmacological and conventional behavioral treatments, the last few years' research has begun to explore the enhancement of time perception abilities in children with ADHD through systematic training. Time estimation is based on attention, working memory, and self-regulation skills - processes usually impaired in children with ADHD. Increasing these early cognitive processes then not only makes children perform better on laboratory tasks but also estimate time more accurately, sensibly plan daily routines, and manage homework schedules in real life. Therefore, many researchers have added neurofeedback to cognitive computer games to treat time perception deficit and attention deficits in children with ADHD.

Neurofeedback is a subtle brain training technique that helps children learn to manage brain function by watching real-time electroencephalogram (EEG) activity. The system provides feedback through animation, sound, or reward cues

when the brain activity of children matches pre-established target patterns when they are engaged in tasks or games. This training encourages kids to become proficient in focusing and self-regulation. Mental computer games, on the other hand, are designed to train working memory, attention, cognitive flexibility, and time appreciation through structured activities. Special training tasks include a time estimation game, in which children estimate the duration of events appearing on the screen; a rhythm synchronization task, in which children mimic rhythmic flashes or taps to improve time intervals; and multitasking switch games, in which children execute several subtasks within a time constraint, thereby exercising attention, time management, and executive functions all at once. By incorporating these thinking activities into neurofeedback, not only is interest stimulated, but repeated practice of attention and time management skills is also enabled within a game-like setting.

The combined method constitutes a new research design that highlights the contribution made through neural plasticity. Through repetitive training with EEG feedback, the child's brain can form new links and increase the perception of time intervals and events sequences. Meanwhile, data recording of the gameplay helps to modify the difficulty level in line with individual performance to enable individualized intervention. This is particularly important for ADHD children, who have individual variability over dramatic impressions concerning attention deficit, impulse control, and competence in perceiving time.

Previous work has been yielding supportive evidence of the validity of this approach. For instance, Moradi et al. [23] found that the combination of neurofeedback with cognitive games significantly affected attention, working memory, and perception of time in children with ADHD. Similarly, Zhong et al. (2024) conducted a systematic review and meta-analysis that indicated neurofeedback training has a significant capacity to enhance executive functions, particularly regulation of attention and working memory, among people. These abilities are highly coupled with time perception because time judgement, rhythm synchronisation, and sustained attention are based on the prefrontal cortex and its related executive networks. Hence, executive functioning improvement can indirectly enhance improved time processing. The combination of neurofeedback and cognitive gaming carries the same logic a step further: by strengthening real-time self-regulation of the EEG and real-time cognitive control simultaneously, children not only learn to focus and suppress but also learn to repeatedly practice time estimation and time management within pre-specified tasks.

Historically, conventional medication has provided rapid symptomatic relief, yet time perception effects were only indirectly obtained with obvious side effects associated with these conventional treatments. Conversely, the combined activities of neurofeedback training and gaming enable specific cognitive impairments to be directly trained, with feedback on real-time information providing strategies for more targeted intervention approaches. Most valuable in these approaches is the capacity to increase the interest levels and motivation in children with fun games providing immediate feedback, hence ensuring high levels of compliance that remain pivotal in the treatment of ADHD in children.

In their daily pursuits, such training could result in children carrying out tasks successfully in activities such as homework organization, in-class focusing, and time allocation in relation

to daily assignments. For example, they are able to estimate task duration more accurately, more consistently adhere to schedules, and more effectively allocate attention when multitasking. At the same time, training together can reduce anxiety, enhance self-efficacy and enhance cognitive flexibility, enabling children not only to perform better on experimental or training tasks but also to plan and control their own behavior on their own in everyday situations. Future studies should be extended to examine long-term effects of such computer game training on various age groups, and explore combining neurofeedback with rhythm training, time estimation tasks, and simulations of everyday situations. Such research may advance the generalizability of training benefits to real life and create new opportunities for ADHD therapy.

7. Conclusion

Impaired time perception is one of the central cognitive features of ADHD, influencing attention, self-regulation, and daily functioning. In behavioral and neuroimaging studies, adults and children with ADHD are found to be incorrectly estimating time intervals and being inconsistent in their timing, which is linked to fronto-striatal and cerebellar circuit pathology and aberrant activity in large networks such as the DMN. Medication reduces some aspects of attention and timing but does not correct these abnormalities. New non-pharmacological treatments, of which cognitive training, neurofeedback, and gaming interventions are some, are demonstrated to be capable of remediating executive function and temporal control. Analysis of how time perception goes awry in ADHD not only sheds light on the brain mechanisms but also opens new vistas to the development of more and more targeted therapies.

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