UNIVERSITY OF PADOVA

Department of General Psychology

Bachelor's Degree Course in TEMPS

Final dissertation

(Basal Ganglia and Time Perception)

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1. Introduction

Many individuals concur that the two basic elements of the human experience are space and time. Plenty of the tasks we perform daily are series of actions, including talking, playing an instrument, or travelling a well-known path. Previous studies have shown that different cortical and subcortical regions are linked to the generation of sequential movements(1). Fluent performance of many sequential activities requires carrying out component actions in the appropriate order and in the appropriate temporal relation to one another. While the understanding of spatial processing has advanced significantly, less is known about the neurological underpinnings of temporal processing. Numerous lines of evidence indicate that basal ganglia play a critical role in timing(2).

1.1 Historical perspective

In the twenty-first century, research on time perception has advanced from conceptual models to complex neuroscientific investigations, with a primary focus on the neural underpinnings of temporal processing. The critical role that the basal ganglia play in the brain's timing systems has been highlighted by the detailed investigation of these mechanisms made possible by the development of improved neuroimaging tools. The dynamic interaction between attention and time perception has been explained by (Coull & Nobre, 2008)(3), who have provided an illustration of how brain networks control the perception of time intervals. This was further developed by (Wiener et al., 2010)(4), who showed the different brain pathways that are involved in the perception of time intervals ranging from sub-seconds to minutes, involving the basal ganglia among other structures. Our knowledge has been further enhanced by a research by (Merchant et al., 2013)(5), which provides an extensive overview of the brain underpinnings of timing and time perception across several sensory modalities and temporal scales. All things considered, these studies show how complex temporal processing is, showing how the brain's timing architecture is closely related to cognitive functions like expectation, memory, and attention, with the basal ganglia acting as a crucial hub for the coordination of these processes.

1.2 Theoretical frameworks

The theoretical frameworks for time perception provide a mechanistic understanding of how temporal information is processed in the brain, have greatly expanded our understanding of time perception. They draw attention to the intricacy of timing mechanisms, which entail comparison and storage of temporal memories in addition to the integration of sensory inputs, psychological state regulation, and interval counting. The brain underpinnings of these theories should be further clarified by future research using neuroimaging and computer modelling, which could result in a more comprehensive theory of time perception. Particularly the pacemaker-accumulator model and the concept of an internal clock, offer insightful perspectives on how the brain manages the perception of time. These models, while distinct, share the fundamental proposition that time perception is governed by internal mechanisms that can be conceptualized in terms of clocks or counting processes.

The pacemaker-accumulator model evolving from the Scalar Expectancy Theory (SET) (6), posits that an internal pacemaker emits pulses at a regular rate, which are then counted by an accumulator. The number of pulses accumulated within a certain interval is used to estimate the duration of that interval. The flow of pulses can be modulated by various factors, such as attention and arousal, which in turn affect the perceived duration; increased attention to time or higher arousal levels can lead to faster pacemaker rates, and thus, longer perceived durations. This model has been supported by empirical research showing that the perceived duration of events can be stretched or compressed based on psychological states, highlighting the brain's adaptability in timing(6).

The internal clock model further refines the idea of time perception by suggesting that the brain functions as a clock, with mechanisms for generating, maintaining, and encoding temporal information. This model encompasses the pacemaker-accumulator system but also includes memory components for storing temporal information and decision processes for comparing durations. It suggests that the basal ganglia and cerebellum play critical roles in the functioning of the internal clock, with the basal ganglia involved in the accumulation and storage of temporal information and the cerebellum in the fine-tuning of motor responses based on timing (5,7).

1.3 Basal ganglia

The basal ganglia, a complex network of subcortical structures nestled deep within the brain, have long been a subject of fascination and inquiry among neuroscientists and researchers. The putamen and caudate nucleus (collectively, the striatum), globus pallidus (its internal GPi and external GPe segments), substantia nigra (its pars compacta SNc and pars reticulata SNr), and the subthalamic nucleus (STN) are among the interconnected subcortical nuclei that make up the basal ganglia. The ventral pallidum, ventral tegmental area, and nucleus accumbens make up the limbic region of the basal ganglia. The primary function of the basal ganglia is to select and carry out intentional actions in response to both internal and external stimuli. Above all, voluntary movements are facilitated, and concurrently competitive or conflicting movements are inhibited by the basal ganglia. Additionally, their involvement is connected to the regulation of other intricate non-motor behaviors, such as emotions, language, decision making, procedural learning, and working memory(8). However, an emerging body of evidence suggests that the basal ganglia's influence extends beyond motor functions to encompass cognitive and perceptual domains, including the perception of time(9).

Both laypeople and scientists frequently use the term "timing" to describe when something happens as well as how long it lasts (estimation of duration). Predicting the likelihood of an event can help determine its onset or offset, as well as whether it happened before or after a specific temporal landmark (temporal order judgement). A metrical representation of time, in which the timing (duration or start) of a single event may be measured on a continuous, parametric timeframe, is necessary for both duration estimation and temporal prediction. Conversely, temporal order judgements necessitate an ordinal representation of time, wherein the relative timing of a minimum of two occurrences is contrasted with each other in a significantly more categorical fashion. Recent studies have proposed that the basal ganglia play a pivotal role in temporal processing, impacting various aspects of time perception, such as duration estimation, temporal memory, and the ability to distinguish between temporal intervals(9).

1.4 Role of basal ganglia

A Study by (Paton & Buonomano, 2018)(10) highlight the basal ganglia's significance in encoding temporal information and processing time intervals. Additionally, these studies emphasize the synchronization of motor responses with external temporal cues, a key aspect of time perception. The role of dopaminergic signaling in the basal ganglia, as elucidated by (Wiener et al., 2010)(4), further underscores their importance in modulating aspects of time perception, linking motor control with cognitive temporal processing(10). Contemporary models of time perception include modifications of the classical pacemaker-accumulator and internal clock models, integrating recent neuroscientific findings. For instance, (Coull et al.,2011)(6) proposed refinements to the internal clock model, incorporating neural data that suggest a more complex interaction between the motor system and cognitive processes in time perception(9).

1.5 Neuroimaging findings

Considering Functional magnetic resonance imaging (fMRI) findings, the basal ganglia have been thought to play a central, content-free and supramodal role in time perception. Likewise, the cerebellum has been considered to play a significant role in this function. Besides the subcortical activations in the cerebellum and basal ganglia, wide-ranging cortical network activations have been shown during timing tasks. (Bueti et al.,2008a)(11) suggested that the parietal cortex may have a role in perceptual and motor timing, while the extrastriate cortex is responsible for the timing of visual stimulus and movements. (Ferrandez et al.,2003)(12) showed that a stimulus duration comparison task activated the basal ganglia, supplementary motor area (SMA), ventrolateral prefrontal cortex, inferior parietal cortex and temporal cortex. This study suggested that the basal ganglia and SMA are related to the time-keeping mechanisms, while the frontoparietal network might be related to the attention and memory processes required for time perception. In another fMRI study, differences between perception of long and short time durations were examined. The results showed that, compared to short time durations, long time durations caused higher activations in the anterior cingulate cortex (ACC), presupplementary motor area, right frontal gyrus, bilateral premotor cortex and also in basal ganglia(6,11,12).

1.6 Comparative analysis with other regions

Understanding the basal ganglia's distinct role in time perception is improved by including a comparative examination with other brain regions, particularly when contrasting its operations with those of other important regions like the cerebellum and prefrontal cortex. According to recent research, the cerebellum is principally linked to the precise timing of motor responses and the processing of sub-second intervals, whereas the basal ganglia are essential for integrating temporal information and assisting complicated timing tasks(13). This difference points to a functional specialization in which the basal ganglia support a wider variety of timing functions, such as perception and estimation of longer durations, whereas the cerebellum supports the fine-tuning of motor motions in time.

Moreover, the prefrontal cortex (PFC) is essential for the cognitive components of time perception, including the conscious knowledge of time passing, working memory involvement in temporal judgements, and decision-making based on temporal information(4). The involvement of the PFC suggests a higher-order integration of temporal information with cognitive processes, in contrast to the more basic mechanisms of timing attributed to the cerebellum and basal ganglia.

Furthermore, the interplay among these areas, facilitated by intricate brain pathways, emphasizes the holistic aspect of temporal perception, necessitating the synchronization of sensory data, motor strategy, and cognitive assessment.

1.7 Degenerative disorders

To date, all the neuropsychological studies examining the role of the basal ganglia in sequence learning have involved patients with degenerative disorders, either Huntington's disease(14) or Parkinson's disease(15). While these disorders have proven to be useful models for studying basal ganglia dysfunction, it is important to keep in mind that these diseases produce both direct and indirect changes in cortical function(1).Recent research has sought to identify the sources of individual differences in sensorimotor synchronization skill by combining behavioral experimentation with computational modeling. Behavioral experiments on sensorimotor synchronization typically employ laboratory tasks that require repetitive movements (e.g., finger taps or drum strokes) to be produced in time with sequences of auditory or visual events generated by a computer(16–19).

By integrating findings from studies in psychology, neuroscience, and related disciplines, we aim to provide a holistic perspective on this multifaceted topic. This review will encompass research from various methodologies, including neuroimaging studies, neuropsychological investigations, offering a multidimensional understanding of the basal ganglia's role in time perception also demonstrating how such impairments can lead to altered perception of time intervals and challenges in temporal memory. Furthermore, it will consider both healthy populations and those with basal ganglia-related disorders, providing insights into both the normal functioning of this system and how it can go awry.

2. Methods

Focused questions that were created according to the participants, intervention, control and outcomes (PICO) principle.

Question: Does a lesion in the basal ganglia affect time perception?

(P) Participants: It was a determining factor that participants had a lesion in the basal ganglia.

(I) Type of intervention: The presence of basal ganglia lesions affecting any structure whether its caudate nucleus, putamen or globus pallidus.

(C) Control or (comparison): healthy individuals.

(O) Outcomes: measurements of time estimation, time production, time reproduction, or reaction times in temporal tasks.

Eligibility criteria

All types of primary observational study designs (i.e Cross-sectional, cohort, systematic reviews, case reports) were eligible for inclusion. Eligible participants were patients diagnosed with basal ganglia lesion with no gender restrictions.

Literature search protocol (Evidence gathering and study selection)

- Pubmed/Medline and Google Scholar were searched with a predetermined strategy. When the search results were small, search terms were reduced to maximize the search sensitivity.

- Multiple Journals and websites were manually searched for relevant articles, databases were searched from 2010 to 2022 using different combinations of the following terms "basal ganglia", "time perception" and "temporal impairment". Full texts of studies were deemed accepted based on title and abstract were read and independently evaluated for the stated eligibility criteria. Hand searching of reference lists of bibliographies of papers with potentially relevant original and relevance were subjected to the same screening and selection process.

This systematic review was made in order to summarize the relevant data. Initial search yielded 11 studies; 4 studies that did not fulfill the eligibility criteria were excluded. In total 6 experimental clinical studies and case reports were included and processed for data extraction in the following table.

Authors	n° Patient	Age mean	n° control	Age mean	Timing task	Modality	Range (temporal intervals)	Type of data (RT, Accuracy)	Results
Aparicio 2005	6	66.2	11	62.5	Maximum speed	nan	nan	intertap interval	Reduced accuracy in patient
Aparicio 2005	6	66.2	11	62.5	Timed controlled movements	auditory	400 ms	intertap interval	No significant difference
Aparicio 2005	6	66.2	11	62.5	Timed controlled movements	auditory	Random	intertap interval	No significant difference
Aparicio 2005	6	66.2	11	62.5	Force control	visual	800 - 1200	target force(N)	No significant difference
Coslett 2010	2	51	13	52	Interval estimation	visual/ auditory	2,4,6,8,10,12	stimulus durations	No significant difference
Coslett 2010	2	51	13	52	interval production	visual/ auditory	nan	stimulus durations	No significant difference
Coslett 2010	2	51	13	52	interval reproduction	visual	2,4,6,8,10,12	stimulus durations	No significant difference
Coslett 2010	2	51	13	52	Interval assessment	visual	200, 600, 2000, 8000	Longer/Shorter	No significant difference
Coslett 2010	2	51	13	52	timed repetitive	auditory	400	stimuli replication	more variability in patients
Nozaradan 2017	11	50.9	11	52.1	Detect Auditory Change	auditory	33	neural activity	No significant difference
Schwartze 2011	10	46.7	10	46.7	Spontaneous motor temp	nan	nan	number of taps	more variability in patients
Schwartze 2011	10	46.7	10	46.7	Sensorimotor synchronization	auditory	600 +- 30,45,60,75	detect change	Reduced accuracy in patient
Schwartze 2015	30	55.2	30	55.4	Inter-stimulus intervals	auditory	600	deviance count	Reduced accuracy in patient
Schwartze 2015	30	55.2	30	55.4	Inter-stimulus intervals	auditory	Random	deviance count	Reduced accuracy in patient
Shin 2005	4	64.8	7	67.7	Serial reaction time	visual	200,300, 500,800	median reaction time	No significant difference

Authors	n° Patient	Age mean	n° control	Age mean	Timing task	Modality	Range (temporal intervals)	Type of data (RT, Accuracy)	Results
Shin 2005	4	64.8	7	67.7	fast tapping	auditory	nan	mean intertap interval	Reduced accuracy in patient
Shin 2005	4	64.8	7	67.7	fast tapping	auditory	nan	intertap interval	Reduced accuracy in patient
Van der Steen 2015	15	60	15	60	sensorimotor synchronization	auditory	600	asynchronies	Reduced accuracy in patient
Van der Steen 2015	15	60	15	60	sensorimotor synchronization	auditory	600 to 387	prediction/tracking ratio	Reduced accuracy in patient

3. Discussion

The information taken from multiple study publications provides a complex picture of the function of the basal ganglia in time perception, particularly when considering the age, number of patients, features of the control group, and results obtained from different tasks. Notably, the research cover a wide range of temporal tasks across several modalities (auditory and visual), including maximum speed, timed controlled movements, force control, interval estimate, and sensory synchronisation. A thorough examination of how temporal processing abilities are impacted by basal ganglia injuries is made possible by the variety of experimental methods used. The age range of the patients and the comparison with age-matched controls offer a vital starting point for comprehending the lifetime effects of basal ganglia dysfunction. For example, Aparicio (2005) and Coslett (2010) findings suggest that while some tasks revealed reduced accuracy or increased variability in patients, others showed no significant differences compared to healthy controls. This indicates that the basal ganglia's involvement in time perception may be more complex and task-dependent than previously thought.

Building on these findings, the inconsistent findings from various studies highlight the significance of taking task-specific variables and sensory modalities into account when assessing the basal ganglia's role in time perception. In activities like interval estimate or timed repetitive movements, where no significant changes were observed between patients and controls, it is possible that some aspects of temporal processing are still intact even in the presence of basal ganglia dysfunction. However, the lower accuracy and more variability in other tasks emphasise how important the basal ganglia are for regulating timing and fine-tuning temporal precision. These results call for a more thorough investigation of the underlying mechanisms, which may include brain oscillations, dopaminergic modulation, and the integration of sensory data. This could clarify the complex function that the basal ganglia play in temporal cognition. Moreover, the data points towards the need for further research incorporating a wider array of tasks, more diverse patient demographics, and longitudinal studies to fully understand the complexities of time perception and its neural substrates.

The complex details of the data displayed in the table make it clear that a wide range of parameters, such as the age of the participants, the clinical characteristics of the patient group, and the particulars of the temporal task, have an impact on the involvement of the basal ganglia in time perception. The varied effects of basal ganglia dysfunction on tasks requiring motor vs cognitive time, for example, indicate that the basal ganglia have diverse neural routes and processing systems for different kinds of temporal information. This specialization is consistent with ideas that suggest the brain has several timing systems, each specialized to operate in different temporal domains or scales. Results such as those of Wiener et al. (2010)(4) support this viewpoint by showing that the basal ganglia are involved in both the encoding and retrieval of temporal intervals throughout a variety of durations. The age-related study adds to the complexity by raising the possibility of a decline in these brain systems' effectiveness with ageing, which may be made worse by illnesses affecting the basal ganglia. This emphasizes how crucial it is to create age-appropriate evaluations and treatments to deal with timing deficiencies.

Furthermore, the differences in outcomes between study patient and control groups highlight the diversity of illnesses affecting the basal ganglia and how they affect sense of time. The preservation of timing abilities in certain tasks or populations could be explained by compensating brain mechanisms, indicating an adaptive ability within the larger neural network that includes the basal ganglia. Subsequent investigations ought to focus on defining these compensatory pathways. This may involve utilising sophisticated neuroimaging and computational modelling methods to describe the dynamic interplay among the brain's timing networks. Furthermore, combining results from pharmacological research may provide light on how dopamine-related neurotransmitter system modulation may affect temporal processing and open up new treatment options for basal ganglia illnesses that cause timing impairments.

The conclusions drawn from the table data have significant therapeutic consequences, especially when it comes to the identification and management of illnesses affecting the basal ganglia. The sophisticated knowledge that distinct components of time perception can be significantly impacted by malfunction of the basal ganglia creates new opportunities for focused therapies. For example, the identification of particular deficiencies in temporal processing may result in more individualised therapy methods in diseases where basal ganglia dysfunction is a hallmark, such as dystonia, Parkinson's disease, and Huntington's disease. The specific parts of timing that are impacted could be addressed by rehabilitation treatments that use pharmacological manipulation, neurofeedback, or cognitive training to improve temporal processing. In addition, comprehending the correlation between the degree of damage to the basal ganglia and the magnitude of timing impairments could provide new biomarkers for the advancement of the disease and the effectiveness of treatment. This could lead to the incorporation of temporal tasks into regular neurological evaluations, thereby improving the monitoring of patient outcomes.

Looking forward, there are various interesting possibilities for further investigation in the realm of time perception research, particularly with relation to the basal ganglia. Developments in non-invasive brain stimulation techniques (e.g., TMS, tDCS) and neuroimaging methods (e.g., high-resolution fMRI and PET) provide tools for mapping the fine-grained neural networks involved in timing and manipulating their activity to evaluate functional contributions. Furthermore, the use of artificial intelligence and machine learning into data analysis may reveal patterns and relationships that were previously overlooked, which would make it easier to create predictive models for temporal processing deficiencies in neurological disorders. Furthermore, transdisciplinary studies integrating genetics, molecular biology, and cognitive neuroscience may clarify the underlying genetic predispositions and biological pathways influencing time perception and related problems. In conclusion, these cutting-edge techniques combined with cross-cultural and longitudinal research will expand our knowledge of the function of the basal ganglia in time perception and open the door to novel therapies and diagnostics in the field of neurology and other fields.

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