UNIVERSITÀ DEGLI STUDI DI VERONA

DEPARTMENT OF

FOREIGN LANGUAGES AND LITERATURES

DOCTORAL PROGRAMME IN

LINGUISTICS

Cycle XXXVIII / Academic Year 2022/2023

FROM WORDS TO DIAGNOSIS: EXPLORING THE PREDICTIVE POTENTIAL OF LANGUAGE COMPETENCE AND IMPLICIT LEARNING IN PARKINSON'S DISEASE

S.S.D. GLOT-01/A Glottologia e linguistica

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Acknowledgements

This thesis would not exist had I not encountered a number of extraordinary people who made it not only possible, but even enjoyable. To all of you, I owe my deepest gratitude. And I would invite the reader to sit comfortably.

Denis Delfitto, you ignited my passion for research and shared your enthusiasm so generously that I could not leave my scientific curiosity unsatisfied. My *Doktorvater* and a constant throughout this journey, in the mathematical sense.

Maria Vender, your rare ability to combine exemplary scientific commitment together with genuine kindness has been an inspiration and everything one would wish for in an advisor.

I am profoundly grateful to the people of the Department of Neurosciences, Biomedicine and Movement Sciences at the University of Verona and Azienda Ospedaliera Universitaria Integrata Verona. In particular, Michele Tinazzi, Ilaria Di Vico, my role model when I first stepped into the hospital, unaware of how enriching that experience would become, Mirta Fiorio, Marialuisa Gandolfi, Angela Sandri, and Angela Marotta.

To Gesa Hartwigsen, Simona Mancini, and Maria Teresa Guasti: thank you for your constructive feedback on my dissertation, for your continued trust in my ideas and skills, and for your pragmatic guidance. I value your support deeply.

I am sincerely thankful to all those who offered feedback on my work at various stages, including at conferences or through collaborations. Chiara Melloni, Christina Manouilidou, Vitória Piai, Max Canzi, Tamara Rathcke, István Kecskés, Christelle Lacassain, Elena Barbieri, Andrea Padovan, Sabrina Bertollo, Stefan Rabanus, Alessandra Tomaselli, Jost-Julian Rumpf: I am deeply grateful for your insights and exchanges.

To my colleagues and friends, who made this journey exciting in more ways than I can count: thank you. Sara Cavaglià, we shared every moment of the PhD, and I hope we will share much of what is yet to come. Marta Tagliani, thank you for the synergy on teaching duty and for letting me in one of the most joyful moments of your life. Ilaria Venagli and Andrea Nardon: thank you for every conversation we had, mutually blowing on our research flames, and for the affinity we share, which made me feel extremely lucky and understood. Lorenzo Severini, thank you for your coding tricks, the legacy, and your commitment beyond traineeship duties. Francesca Bottura, Arianna Favaretto Cortese, Vlado Jelcic, Lorenzo Ferroni, Umberto Costantini, Gabriele Vezzani, Fabio D'Asaro, Angelica Zordan, Veronica Girolami, Natasha Shirokorad, Katharina Knapp, Letizia De Togni, Eleonora Morei, Laura Narisano, Enrica Zaninotto, Mariana Gonzalez Zambon, Arianna Compostella, Carlo Zoli, Luigi Pavone, Irene Lozzi: thank you for your presence along the way.

My gratitude also goes to the brilliant minds at the Max Planck Institute for Human Cognitive and Brain Sciences and Leipzig University. Anna-Lisa Schuler, Andrea Bruera, Gerasimos Gerardos,

Maria Samara, Robin Gerrits, Katie Williams, Vivien Barchet, Sandra Martin, Ole Numssen, and Christoph Mühlberg: thank you for making me feel at home from day one.

To all the participants in my experiments, people with Parkinson's, their spouses, healthy individuals of all ages: thank you. Each of you contributed to scientific progress by generously donating your time. Without you, nothing written in this dissertation would have been possible.

Roberta Gorgoglione, for all the reasons you know better than anyone else.

Philipp Kuhnke, for all the light you carry.

To my parents, Maurizio Panozzo and Gemma Chiomento: every day I am reminded how proud I am to be your child.

To the dear ones I lost during my PhD. To Miretta Amort, who would have loved to see this completed. My path would have been so profoundly different that this dissertation might never have been conceived (at least, not by me).

Alla mia nonna Bruna, I miss being called "cara a me putea" and I miss everything else, too. I hold you close to my heart.

What an achievement. It belongs not only to me, but to all of you and to everything you have given me along the way.

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Introduction

Parkinson's disease (PD) is traditionally considered a motor disorder, but current medical research increasingly adopts a systemic perspective on this condition, acknowledging that non-motor symptoms are also present. Albeit more subtle, they precede motor symptoms in the time course of disease progression. For this reason, focusing on non-motor symptoms is critical to accelerate disease detection and might represent a paradigm shift in PD diagnosis, which is currently clinical- and motor-based.

One specific type of non-motor symptom concerns language competence. Starting from the '60s, in the last decades much emphasis has been put on Parkinsonian dysarthria, a motor speech disorder that affects articulation and results in changes in voice quality and imprecise speech. This type of motor-related linguistic change is acknowledged by the Movement Disorder Society (MDS) in its Unified Parkinson's Disease Rating Scale (UPDRS), the gold standard for assessing PD severity and progression. However, linguistic symptoms are not limited to those of the motor type. On the contrary, they also encompass non-motor, cognitive aspects of language, as PD has been shown to affect multiple linguistic domains (see Panozzo Chiomento, Vender, & Delfitto, 2026, for a systematic review).

Another non-motor domain of interest is implicit learning, a domain-general skill flexibly recruited during multiple processes, including language. The extent to which implicit learning is impaired in PD remains controversial. Evidence suggests that implicit learning is not globally impaired but depends on task characteristics and on participant-specific factors, such as cognitive status and treatment state.

In this interdisciplinary work, bridging linguistics and medicine, we devised an experimental paradigm to evaluate language competence and implicit learning in a cohort of individuals with PD and in neurotypical controls of two age groups. One group was matched to the clinical population on the key demographic variables (age, biological sex, education), while the second consisted of younger adults. This design enabled us to investigate how the two cognitive capacities evolve over time in healthy ageing and PD pathology.

The ultimate goal of this work is to evaluate language competence and implicit learning as potential predictors of PD, thereby addressing the challenge of diagnostic delay. While the present dissertation focuses on individuals already diagnosed on clinical and motor grounds, future research could extend these findings by assessing the robustness of the identified predictors, examining their accuracy, sensitivity, specificity, positive predictive value, negative predictive value. Additional studies could investigate their role in differential diagnosis between idiopathic PD and other neighbouring pathologies, as well as their presence in individuals bearing genetic mutations associated with familial forms of PD. Such work would allow us to see if language competence and implicit learning are also predictive in at-risk populations.

Taken together, these measures, particularly when combined with other critical non-motor symptoms (e.g., sleep disturbances, olfactory impairment, neuropsychiatric manifestations such as depression, apathy, or anxiety, and autonomic or gastrointestinal dysfunction) in a symptom-clustering approach, may accelerate diagnosis, prevention, monitoring, and access to treatment. A validated collection of symptoms with high predictive value could ultimately serve as a scalable screening tool for the general population.

In the broader context, the world population has never been older and has never aged at such a rapid pace. In these unprecedented times, research on age-related conditions is more crucial than ever.

Beyond its immediate clinical implications, this work also addresses broader theoretical questions, such as: What is the role of subcortical structures (particularly the basal ganglia) in the language system? What is the role of dopamine in modulating linguistic and cognitive functions? How do language processing and domain-general mechanisms interact in both healthy ageing and pathological conditions? How does the trajectory of healthy ageing compare to PD pathology in shaping language and implicit learning mechanisms, and what compensatory processes might be at play? What insights does evidence from the PD population provide on theories on grounded cognition, which explore the relationship between language and physical experience?

This dissertation is organised into three parts: Part I provides the theoretical background; Part II presents three experimental studies; Part III offers a general discussion, integrating theoretical perspectives with our novel experimental findings to draw conclusions and outline directions for future research.

PART I – THEORETICAL BACKGROUND

Because Parkinson's disease (PD) is both a neurological and a cognitive disorder, this work adopts a strongly interdisciplinary perspective. Language and other cognitive deficits, in fact, cannot be understood in isolation but must instead be contextualised within the clinical profile of PD, its neuroanatomy, and relevant theories of cognition and language. Therefore, Part I provides the conceptual background necessary to situate the present experimental work within both clinical neurology and linguistics.

At the same time, this section also lays the foundation for the central contribution of the dissertation: a new account of lexical access in PD that integrates the analysis of linguistic features such as action-relatedness, argument structure and *qualia* structures with an exploration of a domain-general capacity, namely implicit learning skills.

The structure of this part is as follows: Chapter 1 reviews the medical foundations of PD; Chapter 2 presents the state of the art in research on language competence in PD; Chapter 3 examines implicit learning mechanisms in PD; and Chapter 4 identifies the open questions that guide the experimental studies presented in Part II.

Chapter 1 – Parkinson's Disease: A Clinical and Diagnostic Overview

1.1 Introduction

This chapter provides an overview of the state-of-the-art medical research on PD, summarising current knowledge while also highlighting the unknowns about this condition. The insights presented here are drawn from clinical neurology literature, but also from stakeholders and foundations. These perspectives serve as groundwork for the interdisciplinary research presented in the following chapters, which focuses on language and other cognitive aspects in individuals with PD and aims to identify novel predictors capable of facilitating an earlier diagnosis of the disease.

1.2 Defining Parkinson's Disease

Parkinson's disease (PD) is a progressive neurodegenerative condition ascribed to movement disorders and, in particular, hypokinetic movement disorders. It was first fully clinically described in 1817 by James Parkinson, an English physician who referred to it as "the Shaking Palsy" or *Paralysis Agitans* (Parkinson, 1817/2002), and after whom the disease is now named. However, accounts of this medical condition existed long before this classical work of neurology, and not only in the Western world, with sources dating back to more ancient times, including India around 1000 BCE, where it was described under the name *kampavata* (kampa: tremor) (Manyam, 1990), as well as traditional Chinese texts from around 300 BCE, in which it was referred to as the "liver wind" (Zhang et al., 2006). An even earlier reference to PD-compatible symptomatology, albeit more speculative, may be found in the *Ebers Papyrus*, the longest and most significant of the ancient Egyptian medical papyri discovered so far. Dating to around 1550 BCE and currently housed in the Leipzig University Library, it may stand as the oldest known attestation of such symptoms (Halioua & Ziskind, 2002).

Throughout history, a number of notable figures and observers offered descriptions of movement that scholars later associated with PD. In chronological order, the Greek physician Galen, the most influential medical thinker of antiquity after Hippocrates, recognised symptoms such as tremor and gait disorder (Stern, 1989). During the Renaissance, Leonardo da Vinci recorded movement irregularities in his anatomical manuscripts dated between 1485 and 1515 (Calne et al., 1989). Around 1600, William Shakespeare reported similar signs in *Henry VI*, *Part 2* (Voss, 2012). In 1680, the Dutch physician and anatomist Sylvius de la Boë discussed comparable symptoms in his *Opera Medica* (Goetz, 2011). The English philosopher Thomas Hobbes is also believed to have suffered from PD (Malcolm, 2002), and his letters presented micrographia, one of the hallmark symptoms of PD characterised by abnormally small handwriting. Similarly, in the 19th century, the linguist and educational reformer Wilhelm von Humboldt documented his own disease in letters to a friend written between 1828 until his death in 1835 (Horowski et al., 1995). Following Parkinson's foundational work, the French neurologist Jean-Martin Charcot emerged as a central figure in refining the clinical profile of the disease. After reading Parkinson's *Essay* in the 1860s, Charcot examined numerous cases and expanded the diagnostic framework in terms of motor symptoms. Crucially, Charcot also noticed that not all affected individuals presented with tremor, prompting him to rename the condition from "Shaking Palsy" to "Parkinson's disease" (Goetz, 2011).

This brief historical parenthesis is more than a philological exercise. If early descriptions and pre-clinical models correspond to PD as we define it today, this suggests that the disease has existed long before it was recognised and named, and long before industrialisation, and likely had a global distribution. This provides valuable evidence for the research concerned with its aetiology, seeking the triggering causes of the disease. In fact, the aetiology of PD is still unknown, although its causes have been variously attributed. Current research suggests that the disease likely results from a complex interaction between genetic susceptibility combined with environmental exposure (Wirdefeldt et al., 2011). These, however, could be risk factors more than causes. By integrating the early sources attesting PD with the newest epidemiological data, one possibility is that the rarity of early accounts simply reflects lower life expectancy in ancient populations, which would have limited the manifestation of an age-related disorder like PD. In fact, PD is significantly more frequent in world regions with higher life expectancy (Pereira et al., 2024).

In modern epidemiology, there are several possible measures of disease frequency. Prevalence refers to the proportion of individuals in a population who have the disease at a specific point in time, therefore capturing a static snapshot of the probability of having the outcome state. By contrast, cumulative incidence reflects the risk of developing the disease over a specified period, capturing only new cases and thus reflecting a dynamic process. At present, prevalence data from the Parkinson's Foundation estimate that more than 10 million people worldwide currently live with PD. Recent epidemiological studies show that the prevalence of the disease is steadily rising, making it the fastest-growing neurodegenerative condition globally (Zhu et al., 2024). This upward trend is strongly associated with population ageing and longer life expectancy of the global population (Li et al., 2021), reinforcing the urgency of conducting research on this age-related condition.

There are important patterns in PD distribution and connected to demographic factors, with some geographic variation (Zhang & Román, 1993). Incidence increases significantly after age 60 (de Lau & Breteler, 2006), with age representing the most critical risk factor and a key determinant of clinical progression (Levy, 2007). Humans are the only animals that contract PD naturally (Diederich et al., 2019). Biological sex plays a role, as the disease is more prevalent in men compared to women (Cerri et al., 2019), and educational attainment may influence the risk of developing PD (Frigerio et al., 2005).

Turning to definitions, Albin (2023) describes PD as:

> "An age-related neurodegenerative syndrome characterized primarily by clinical features of parkinsonism, notably bradykinesia, consequent to relatively selective, early degeneration of dopaminergic nigrostriatal terminals. It is gradually progressive over the course of several years. Its early clinical features are driven by striatal dopaminergic denervation with prominent later clinical features secondary to extrastriatal pathologies".

This definition emphasises that PD occurs with ageing and involves neurodegeneration. It makes reference to its motor clinical symptoms, in particular bradykinesia, or slowness of movement characteristic of PD. It also refers to its pathophysiology, mentioning the underlying mechanisms that lead to the development of the disease. In particular, one of the key early pathological hallmarks of PD is the degeneration of dopaminergic nigrostriatal terminals, which disrupts signalling between the substantia nigra region and the striatum. The clinical course of the disease progresses slowly over many years: its early symptoms arise from dopamine loss in the striatum, while its later symptoms reflect a more widespread extrastriatal pathology.

While informative and adopted as a provisional working definition in the present research, this characterisation largely emphasises the motor symptoms of PD and does not fully capture the period preceding motor manifestations and clinical diagnosis. PD is a complex condition that also involves a lengthy "preclinical stage", namely the period during which neurodegeneration is underway, but no clinical manifestations are evident, and a "prodromal stage", marked by non-motor symptoms that are currently insufficient for the purposes of a formal diagnosis (Bhatia et al., 2017). These pre-motor stages should be accounted for to render the complexity of PD, as they are critical for early disease detection and the potential implementation of disease-modifying treatment (Olanow & Obeso, 2012).

As research continuously refines our understanding of the disease, it is paramount to consider that formulating a definition is not a trivial task, and that traditional definitions get challenged, highlighting the need for some definitory work and dynamic approaches (Berg et al., 2014). A holistic perspective that integrates motor and non-motor dimensions, and reflects the clinical heterogeneity of PD is indeed essential for an accurate and encompassing definition of PD.

1.3 Motor and Non-Motor Symptoms (and Cognitive Profile)

The motor nature of PD has been put in the foreground ever since the early sources reporting it. However, from the point of view of its symptomatology, this condition is now recognised as "systemic", meaning that it is a multifaceted neurological disorder that presents both motor and non-motor symptoms (Chaudhuri & Schapira, 2009). Despite being initially disregarded by the initial observers (Parkinson, 1817/2002), non-motor deficits are now not only recognised as part of PD clinical presentation, with modern descriptions of the disease going beyond its simple motor manifestations, but also acknowledged as preceding motor signs (Postuma et al., 2012). Non-motor symptoms, although under-recognised due to their subtlety and lower level of diagnostic specificity, are now an essential part of the clinical picture of the disease. They include affective symptoms (depression, anxiety, apathy, psychosis, impulse control disorders), autonomic dysfunctions (urinary, sexual, gastrointestinal issues), sleep disturbances, pain, fatigue, and cognitive impairment (Rodriguez-Blazquez et al., 2020; Antelmi et al., 2025; Tinazzi et al., 2025). It is noteworthy mentioning that some affective non-motor symptoms such as anxiety and depression, which are frequent comorbidities of PD, may exert a negative influence on cognition (Park et al., 2020; Cohen et al., 2015).

The hallmark motor symptoms of PD are more evident and comprise the so-called parkinsonian triad, encompassing bradykinesia (slowness), resting tremor, and rigidity, which are still currently used for clinical diagnosis (Postuma et al., 2015). Other motor symptoms include postural imbalance, walking difficulties, freezing of gait, stiffness, dyskinesia (involuntary movement) (Postuma et al., 2015). One key feature of PD motor onset is its lateralised presentation, meaning that symptoms often start on one side of the body (clinicians often refer to it as the "most affected side"). This reflects the asymmetric degeneration of nigrostriatal pathways, with the most affected limbs corresponding to motor cortex involvement in the contralateral hemisphere. The asymmetry also seems to be associated with handedness, with PD initial motor symptoms emerging more often on the side of the dominant hand. Some researchers suggested that because the dominant hemisphere relies more heavily on nigrostriatal dopamine, it may be more susceptible to degeneration, contributing to the observed laterality of the disease (Riederer et al., 2018).

From a neuroanatomical perspective, PD is characterised by the progressive degeneration of dopamine-producing neurons in the substantia nigra pars compacta (SNpc), leading to reduced dopamine input in the striatum, a critical structure in the basal ganglia (Parent & Parent, 2010; Chen & Tansey, 2011). This dopaminergic depletion disrupts the cortico-basal ganglia-thalamo-cortical (CBGTC) circuit and, in particular, the balance between its direct (facilitatory) and indirect (inhibitory) pathways (Obeso et al., 2008; Lindenbach & Bishop, 2013). In PD, the underactivation of the direct and overactivation of the indirect pathway result in reduced excitatory output to the motor cortex, causing the typical hypokinetic symptoms. Since the basal ganglia not only modulate motor function, but they also interact with prefrontal and limbic areas, they also influence cognitive and emotional processes and lead to widespread consequences across motor, cognitive, and affective domains (Wichmann & DeLong, 2007).

Symptom severity, the resultant functional disability and the clinical stage of PD are routinely assessed by neurologists employing a standardised evaluation scale, the Unified Parkinson's Disease Rating Scale (UPDRS), which was established by the Movement Disorder Society (MDS) (Goetz et al., 2008), and which incorporates and expands the earlier Hoehn and Yahr Scale (Hoehn & Yahr, 1967). The MDS-UPDRS is composed of four parts: UPDRS-I (non-motor aspects of daily life experiences), UPDRS-II (motor aspects of daily life experiences), UPDRS-III (motor evaluation), UPDRS-IV (motor complications). The typical disease progression unfolds through a preclinical (latent) phase, a prodromic phase (in which non-motor symptoms are predominant), followed by motor symptoms onset and consequent diagnosis, with potential later development of mild cognitive impairment (PD-MCI) and dementia (PDD) (Emre, 2015). Several phenotypes of the disease have been identified based on its motor features: tremor-dominant, akinetic-rigid, and mixed phenotypes (Schiess et al., 2000), although other criteria are also available for subtyping purposes, some of them also based on non-motor features (Marras & Chaudhuri, 2016). When describing phenotypic variants based on non-motor symptoms, the following domains are considered: cognitive, neuropsychiatric, sleep, olfactory, autonomic (Sauerbier et al., 2015).

Cognitive impairment is a prevalent non-motor symptom of PD and may occur not only in later stages of the disease (Roheger et al., 2018), but also in its early, untreated stages (Weintraub et al., 2015). The following section outlines a cognitive profile of PD, intentionally leaving language aside, as it will be extensively examined in the next chapter. The most commonly affected domains include attention, executive functioning, memory, visuospatial abilities, and social cognition.

Neuroimaging studies have identified attentional control in the visual domain primarily within the frontoparietal system (Scolari et al., 2015). One influential framework for understanding attention is Posner and Petersen's tripartite model (1990, updated 2012), which distinguishes three distinct networks: the alerting network (right-lateralised, involving locus coeruleus and thalamus), the orienting network (intraparietal sulcus, frontal eye fields) supporting top-down spatial attention (Corbetta & Shulman, 2002), and the executive control network (dorsolateral prefrontal cortex and anterior cingulate cortex). This model was operationalised in the Attention Network Test (ANT) assessing the behavioural efficiency of each network through a visual cueing and flanker paradigm (Fan et al., 2002). Nondemented people with PD assessed using the ANT displayed hyperactivation of the alerting network, preserved orienting, and impaired efficacy of the executive network compared to controls. Such executive deficits were further exacerbated in PD participants experiencing fatigue (Pauletti et al., 2017). These findings align with broader evidence of executive dysfunction in PD, especially affecting set-shifting, inhibition, and working memory (Owen, 2004; Dirnberger & Jahanshahi, 2013).

Memory impairments in PD are typically attributed to retrieval deficits linked to frontostriatal dysfunction rather than hippocampal damage characteristic of Alzheimer's disease. Using the Hopkins Verbal Learning Test – Revised (HVLT-R; Brandt & Benedict, 2001), Weintraub et al. (2015) showed early impairments in verbal learning and delayed recall in untreated individuals with PD (data collected in the context of the Parkinson's Progression Markers Initiative, PPMI). Working memory is often relatively preserved in early stages but becomes more vulnerable as the disease progresses.

Visuospatial deficits are well established in PD, affecting mental rotation, figure copying, and spatial navigation. Such deficits are associated with dysfunction in posterior parietal and occipitotemporal regions and can impact daily life, particularly in tasks involving orientation, driving, and navigating unfamiliar environments (Pagonabarraga & Kulisevsky, 2012; Pereira et al., 2009).

As regards social cognition, nondemented people with PD may exhibit impaired theory of mind, emotion recognition, and empathy. Affective dysregulation, including depression, anxiety and apathy, significantly impairs quality of life while also interacting with cognitive functioning (Leroi et al., 2011).

Cognitive expression in PD is heterogeneous, with differences often observed across different clinical phenotypes. The akinetic-rigid phenotype is more commonly associated with cognitive decline compared to tremor-dominant (Burn et al., 2006). Additionally, sex-based differences in cognitive abilities have also been documented, with women often outperforming men in verbal memory, whereas men may show advantages in visuospatial tasks (Reekes et al., 2020).

1.4 Diagnostic Techniques and Implications

The post-mortem "anatomo-clinical" method is the only definitive means of confirming a diagnosis of PD. This association was first discovered in 1893 by two Charcot's students, Paul Blocq and George Marinesco, who observed abnormalities in the substantia nigra during the autopsy of a man who had exhibited parkinsonian symptoms. In 1919, the Russian neuropathologist Konstantin Tretiakoff noticed that all parkinsonian brains showed extensive damage to the substantia nigra (loss of pigment) and also the presence of small spherical structures that he termed "corps de Lewy" or "Lewy bodies", after a German pathologist working on Alzheimer's disease. Lewy bodies are abnormal agglomerates of the protein α-synuclein, which plays a crucial role in synaptic function and the release of neurotransmitters.

A clinical diagnosis is confirmed by a neurologist and represents the highest attainable diagnostic accuracy in living patients. The criteria established by the International Parkinson and Movement Disorder Society (MDS) still represent the global gold standard for PD diagnosis. The MDS-PD guidelines (Postuma et al., 2015; 2018) heavily rely on the motor features of the disease, bradykinesia, rigidity, and resting tremor, as the foundation for diagnosis. Clinical diagnosis can be supplemented by DaTscan (dopamine transporter SPECT imaging), which visualises striatal dopaminergic deficits. MRI can also assist to exclude structural causes or atypical parkinsonism.

Differential diagnosis is critical, particularly in early stages, to distinguish PD from other parkinsonian syndromes, which include several nosologic entities apart from PD, such as multiple system atrophy (MSA), progressive supranuclear palsy (PSP), corticobasal degeneration (CBD), and vascular parkinsonism (VaP) (Williams & Litvan, 2013).

Although most cases of PD are sporadic, meaning that they occur in isolation and lack a familial pattern, several genetic mutations have been identified and linked to familial forms of PD. These encompass mutations in the PARK1-PARK8 genes, including *SNCA* (PARK1/4), *LRRK2* (PARK8), *PRKN* (PARK2), *PINK1* (PARK6), and *DJ-1* (PARK7) (Hardy et al., 2006). These mutations may cause earlier onset, more aggressive progression, or specific clinical phenotypes. For instance, *GBA1* mutations are associated with a more malignant course of the disease (Höglinger et al., 2022).

There is a large amount of variation in the prognosis for individuals diagnosed with PD. Epidemiological studies conducted in different countries yielded inconsistent results, perhaps due to methodological differences. For example, community-based studies provide accurate data and are less sensitive to biases. Also, studies with no age cut-off provide less biased estimates and allow conclusions to be drawn about early-onset PD. Excess mortality due to PD is also subject to variation due to the heterogeneity of PD itself. A Finnish study reported increased mortality beginning in the first year immediately following diagnosis and rising over 12 years, ultimately reaching 29% excess mortality compared to control subjects. Early-onset PD carried the highest excess mortality rates (Sipilä et al., 2023). Similar trends were obtained in Israel (Peretz et al., 2019), Norway (Hustad et al., 2021), and Korea (Yoon et al., 2021), while studies from Estonia (Kadastik-Eerme et al., 2019) and China (Wang et al., 2022) reported no difference in mortality between PD and controls. PD is a heterogeneous condition, so the different results might be attributed to distinct PD subtypes.

Some factors influence prognosis, among which early detection is particularly important. Current diagnostic research is moving towards the direction of prevention, especially through the identification of biomarkers. A prominent example is the Parkinson's Progression Markers Initiative (PPMI) supported by the Michael J. Fox Foundation.

In recent years, research has focused on identifying reliable biomarkers for early detection, concentrating on non-motor symptoms such as REM sleep behaviour disorder (Antelmi et al., 2021; Stefani et al., 2025), fatigue (Tinazzi et al., 2025), retinal degeneration (Guo et al., 2018), and hyposmia, or loss of the sense of smell (Sui et al., 2019). The olfactory epithelium is of special interest, as its neurons are directly exposed to the environment. According to the Braak Hypothesis (Braak et al., 2003), PD pathology starts in the peripheral nervous system, particularly in the olfactory bulb and the enteric nervous system, before a caudo-rostral (bottom-to-top) spreading to the substantia nigra. This hypothesis is supported by evidence of α-synuclein deposits in enteric and olfactory tissues years before clinical diagnosis.

Although PD is an exclusively human disease, various experimental models have been developed to induce PD in non-human animals (e.g., zebrafish, fruit flies (*Drosophila*), nematodes, rats, mice, macaques, vervet monkeys, squirrel monkeys, baboons and marmosets). To simulate PD-like pathology, researchers have employed neurotoxins (e.g., 6-OHDA, MPTP), pesticides (e.g., rotenone and paraquat) and pharmacological agents (e.g., reserpine and haloperidol) (Duty & Jenner, 2011). These animal models have provided crucial insights into the pathophysiological processes of PD, including dopaminergic neurodegeneration and α-synuclein pathology, and have guided the development of potential neuroprotective and symptomatic treatment (Emborg, 2004; Betarbet et al., 2002).

Symptomatic treatment includes pharmacological therapy, surgical procedures, lifestyle modifications, and supportive care. Pharmacological therapy is based on levodopa, usually administered in combination with carbidopa to improve bioavailability and reduce side effects. Deep brain stimulation (DBS), involving the placement of electrodes either in the subthalamic nucleus (STN) or the globus pallidus interna (GPi) (unilateral or bilateral, in one or both sides of the brain) remains a cornerstone surgical intervention. Such electrodes are connected to a neurostimulator that delivers continuous electrical pulses to modulate neural activity. In recent years, several new techniques gained FDA or EMA approval, including continuous medication infusions, adaptive DBS, and bilateral focused ultrasound. *De novo* PD patients, who are still drug-naïve, represent a valuable cohort for studying disease progression and treatment effects without the confounding influence of dopaminergic therapies.

1.5 Summary and Conclusions

This chapter has provided an overview of PD from its earliest descriptions to its modern clinical and diagnostic practices. PD is an age-related neurodegenerative disorder presenting a complex interplay of motor and non-motor symptoms. While motor signs remain the cornerstone of diagnosis, non-motor features have been demonstrated to precede motor ones, and are therefore critical for early detection. Epidemiological data indicate that PD is the fastest-growing neurodegenerative disease worldwide, with prevalence rising together with population ageing. Its prognosis is highly variable, reflecting the heterogeneity of PD subtypes, but strongly depends on early disease detection. Current diagnostic standards rely on the criteria of the Movement Disorder Society (MDS), and can be supported by imaging techniques. Cutting-edge research increasingly focuses on biomarkers of PD for preclinical identification, as exemplified by the Parkinson’s Progression Markers Initiative (PPMI). Symptomatic treatment, primarily levodopa and deep brain stimulation, remains effective and largely employed to alleviate motor symptoms and protect life quality. Together, these insights highlight the urgency of advancing early detection and personalised approaches to improve outcomes.

Chapter 2 – Language Competence in Parkinson’s Disease

This chapter, which partially draws on Panozzo Chiomento, Vender, and Delfitto (2026), reviews the range of experimental evidence on language competence in PD. Building on the findings of this systematic review, it highlights how linguistic research on PD has so far concentrated more extensively on certain domains, such as phonetics and semantics, while others, including phonology or syntax, have received comparatively less attention. The chapter is therefore structured according to the conventional domains traditionally used for linguistic analysis, from phonetics to phonology, morphology, semantics, syntax, and pragmatics, while giving greater emphasis to those aspects that will be examined more in depth in the experimental part of the thesis. The boundaries between these various subdomains are rather porous, and this pedagogically motivated classification is only adopted for purposes of explanatory clarity. Each section primarily reviews findings from behavioural studies, supplemented by neuroimaging evidence when relevant.

2.1 Phonetics in Parkinson’s Disease

Articulatory phonetics is the domain on which most linguistic research on PD has focused. Changes in voice and speech constitute a hallmark feature of PD (Ho et al., 1999) and are commonly described under the label of *dysarthria*, a motor speech disorder resulting from a defective motor execution of the articulatory processes (Duffy et al., 2015).

Due to the hypokinetic nature of PD, dysarthria typically presents as hypokinetic dysarthria and develops in up to 90% of people with PD (Brabenec et al., 2017). In their systematic review of acoustic studies in newly diagnosed individuals, Brabenec and colleagues (2017) identified characteristic changes in phonation (airflow insufficiency, irregular pitch fluctuations, microperturbations in frequency and amplitude, aperiodicity), articulation (decreased tongue movement resulting in imprecise vowels, imprecise consonants, slow and irregular alternating motion rate), and prosody (reduced loudness, monoloudness, monopitch, inappropriate silences). Clinically, these features manifest as hypophonia (reduced voice volume), monotonic speech, imprecise articulation due to the restricted range of motion of speech articulators, and altered speech rate, resulting in slurred, indistinct, and less intelligible speech. These patterns have been reported cross-linguistically (Kim & Choi, 2017).

The results of objective and subjective analyses of Parkinsonian speech converge in attributing voice disturbances to two main pathological processes in the larynx, namely asymmetric rigidity of the intrinsic laryngeal muscles and incomplete glottic closure due to vocal fold hypokinesis or bowing (Ma et al., 2020).

Recognising the significance of voice and speech impairment in daily life, the MDS-UPDRS section “Motor Aspects of Experiences of Daily Living” includes evaluation criteria for speech-related issues. These criteria encompass the assessment of voice features such as “soft”, “slurred” and "uneven", alongside considerations like the need for repetition during communication and the comprehensibility of speech to the interlocutor.

Given the high prevalence of hypokinetic dysarthria in PD, speech abnormalities can serve as prodromal markers of the disease. Both perceptual assessments by speech therapists (e.g., using the MDS-UPDRS guidelines for speech evaluation) and objective acoustic analysis (e.g., waveform-based machine learning methods) are increasingly used for the differentiation between dysarthric and healthy speech. Recent systematic reviews (e.g., Bang et al., 2023) highlight the value of using machine learning-based acoustic analysis of speech as a non-invasive diagnostic tool.

Importantly, recent studies and reviews (Brabenec et al., 2017; Ma et al., 2020) increasingly indicate the early onset of voice and speech changes, considering them among the earliest signs of motor impairment in PD.

Finally, neuroimaging studies have provided evidence on the neural underpinnings of dysarthria. An fMRI study by Baumann et al. (2018) found that hypokinetic dysarthria was associated with cortical hypoactivation in several speech-related areas. After receiving the logopaedic Lee Silverman Voice Treatment (LSVT), people with PD showed increased right-sided superior temporal activity, which correlated with improved intelligibility.

2.2 Phonology in Parkinson's Disease: A Story of Two Tales

A significant shortcoming in the existing literature addressing phonological competence in PD is a terminological flaw: many studies mislabel phenomena as *phonological* that, in reality, belong to the domain of *phonetics*, particularly articulatory phonetics. What phonology deals with is the mental representation of the sound structure of a language. Despite the considerable attention given to language articulation and dysarthria in PD research, there is a notable paucity of studies focusing on the receptive phonological competence of individuals with PD.

It is fundamental to notice that speech production involves a process of mapping phonological representations and articulatory networks. It is not clear to what extent the articulation deficits identified in PD are motor and to what extent they rely on phonological competence. In other words, PD may not only alter normal-like articulation but also the underlying phonological representation.

Spanish-speaking PD participants were significantly less accurate than controls in tasks tapping their phonological awareness, such as phonological discrimination, syllable segmentation, onset and rhyme detection (Elorriaga-Santiago et al., 2013). Such results were not dependent on other cognitive skills, such as attention, working memory, and long-term memory, to which the identified phonological deficits could not be attributed. Prosodic perception in Italian people with and without PD also showed that PD participants exhibited deficits in this domain, with lower accuracy rates compared to controls in tasks requiring participants to distinguish between accents with non-words, recognising different phrasal intonations (affirmative, exclamative, or interrogative), and discerning emotive intonations

(Garbo et al., 2015). These results, however, might not be merely phonological in nature and might interact with pragmatic processing skills.

2.3 Morphology in Parkinson's Disease

2.3.1 Inflectional Morphology

In addressing morphological aspects of people with PD's language competence, the pioneering study by Ullman et al. (1997) represents the first work based on the hypothesis of a double dissociation between memory types and has been influential in subsequent research dealing with verbal inflectional morphology in PD. In this experiment, researchers tested non-demented (IMC dementia score < 5) PD patients' ability to perform an elicited past tense inflection task featuring twenty pairs of sentences with a gap in the second one: "Every day I dig a hole. Just like every day, yesterday I ... a hole" (Ullman et al., 1997, p. 268). Three experimental conditions for the verb were tested, namely regular, irregular, and novel. The predictions were that, because rule-governed language processes are basal ganglia-mediated functions and because of PD patients' impairment of the basal ganglia, these patients would have been impaired in past tense inflection of regular verbs and unimpaired in irregular verbs stored in their intact temporal and parietal regions. Results demonstrated that PD patients were significantly worse at inflecting regular and novel verbs relative to irregulars, thus confirming the initial predictions.

Verbal inflection in PD has been explored cross-linguistically by several studies using elicitation tasks resembling Ullman's, covering languages such as English (Longworth et al., 2005; Reifegerste et al., 2020), Farsi (Johari et al., 2019b), Dutch (Colman et al., 2009), and modern Greek (Terzi et al., 2005). However, the original results have not always been replicated, as deficits in the PD group compared to neurotypicals did not show selectivity for regular past tense morphology, but also targeted irregular past tense morphology.

Italian, by contrast, represents a particularly interesting testing ground for verbal morphology in PD. Unlike English, which has a relatively poor inflectional system, Italian is morphologically rich, with a complex set of verbal inflections marking person, number, tense, mood, and aspect. Crucially, however, the opposition between "regular" and "irregular" in English past tense morphology cannot be straightforwardly mapped onto Italian. In English, the regular/irregular split interacts neatly with Ullman's declarative/procedural model: the regular past tense is governed by a highly productive default rule, while irregulars constitute a finite list of exceptions that can be memorised. Italian, instead, displays graded levels of morphological productivity, and its so-called "irregular" verbs belong to multiple subpatterns of varying size. As shown in Yang (2016), a work on morphological productivity and the statistical conditions that allow a rule to become generalisable, productivity is not determined solely by whether a pattern has exceptions, but by whether the number and the distribution of those exceptions fall below a threshold that makes the rule computationally advantageous (the Tolerance

Principle). This means that Italian conjugational classes, especially productive participial patterns (e.g., *parlare – parlato*), cannot be assimilated to the English regular/irregular dichotomy, nor do Italian children overgeneralise subregular patterns (not fully productive but forming a cluster with some internal coherence) in the same way that English-speaking children occasionally overregularise the –ed rule for past tense formation.

To the best of our knowledge, no study has been conducted in Italian to test whether individuals with PD and basal ganglia dysfunction show differential sensitivity to these varying degrees of productivity in Italian verbal morphology, for instance between fully productive patterns and forms displaying stem or inflectional irregularities (e.g., *scrivere – scritto*). Investigating Italian would offer an opportunity to determine whether PD selectively disrupts procedural mechanisms tied to productive rules, or whether impairments extend uniformly across morphological patterns regardless of their degree of productivity.

2.3.2 Derivational Morphology

Only a few studies have been dedicated to investigating derivational morphology in PD. Two studies in Italian by Silveri et al. (2018) and Di Tella et al. (2018) were based on a transformation task, in which a verb or an adjective had to be converted into a noun (e.g., *gentile* "kind" into *gentilezza* "kindness", *osservare* "to observe" into *osservazione* "observation"). They also tested the opposite process, which they term "generation" (corresponding to the retrieval of the base), in which the participant is asked to transform a noun into the verb or the adjective from which it derives (e.g., *osservazione* "observation" into *osservare* "to observe", *gentilezza* "kindness" into *gentile* "kind"). The researchers' assumption was as follows: because transforming an element into a noun offers multiple alternatives, this would be the most difficult condition, requiring inhibition of competitive responses. On the contrary, the retrieval of the base form only allows one possible alternative and therefore is less demanding. Experimental results were in line with the predictions, since people with PD and healthy controls were equally quick and accurate in the base retrieval task. However, the PD group was significantly less accurate than the control group in the derivation task ($p < .01$), making some morphological mistakes such as the production of non-existent words employing a wrong suffix (e.g., **osserva-mento* instead of *osserva-zione* "observation") (Silveri et al., 2018). Additionally, people who had PD lateralised on the right side of the body – thus compromising the contralateral hemisphere – were significantly less accurate (66%) in this task than both controls (80%) and people with PD lateralised on the left (77%) (Di Tella et al., 2018). These findings were explained by reference to the linguistic nature of the task, given that the linguistic deficit only emerged when the left hemisphere was damaged (Di Tella et al., 2018).

2.4 Lexical Semantics in Parkinson's Disease

Lexical semantics is a domain of particular interest in PD, as it interfaces closely with the motor system. Differences between PD participants and neurotypical individuals have been investigated in a series of tasks dealing with lexical semantics, such as picture naming (Bocanegra et al., 2015, 2017; Aiello et al., 2022a; Johari et al., 2019a; Isaacs et al., 2019; Salmazo-Silva et al., 2017; Herrera et al., 2012; Cotelli et al., 2007), lexical decision (Fernandino et al., 2013a; Copland et al., 2009; Angwin et al., 2005, 2007), semantic association (Salmazo-Silva et al., 2017; Aiello et al., 2022a; Bocanegra et al., 2015), semantic inhibition (Arnott et al., 2010), and semantic similarity judgment (Fernandino et al., 2013a; Speed et al., 2017; Kemmerer et al., 2013).

In the experimental paradigm of picture naming, subjects are presented with a picture and are asked to quickly and accurately recall the corresponding word by saying it loudly. Lexical access in PD has been deemed compromised by a number of studies, which have investigated naming of both verbs and nouns. Behavioural studies based on accuracy suggested that people with PD have more difficulties when naming verbs that express a high-motion semantics compared to low-motion verbs (Herrera et al., 2012; Bocanegra et al., 2017). For example, verbs ascribed to the high-motion category, such as "to swim", have been found to be more impaired in PD compared to verbs ascribed to the low-motion category, such as "to read". It is crucial to note that "high-" and "low-motion" describe properties pertaining to the conceptual-semantic system, that is, conceptual features which can be analysed independently of their linguistic encoding. This distinguishes them from other dimensions, such as argumental structure, which pertain more directly to the linguistic system. In a similar vein, similarity judgment tasks have demonstrated that people with PD find fast actions, such as "to sprint", more difficult than slow actions, such as "to wander" (Speed et al., 2017). In line with these results, some studies reported that abstract verbs, exemplified by "to depend" and "to improve", are spared (Fernandino et al., 2013a). Another study attributed verb naming difficulties in PD to syntactic rather than semantic reasons, as A-structure (argument structure) complexity of the verbs but not their action-relatedness influenced verbal processing in the PD group (Aiello et al., 2022a). In the study by Aiello and colleagues, non-demented PD participants performed significantly worse than controls in naming both transitive (e.g., "to bite") and unergative verbs (e.g., "to yawn"), whereas no group differences emerged for unaccusative verbs (e.g., "to fall"). These findings support the view that PD may impair processes at the interface with the linguistic system, such as sensitivity to argument structure, rather than being confined to a purely conceptual-semantic deficit, as often proposed in the literature.

As far as nouns are concerned, studies have been conducted in Spanish, Farsi and Italian. People with PD show greater difficulties when naming nouns that express a high level of manipulability, such as *bombillo* "bulb" and *qashoq* "spoon", compared to nouns with low level manipulability, such as *humo* "smoke" and *kooh* "mountain" (Bocanegra et al., 2017; Johari et al., 2019a). Cotelli and colleagues (2007), however, reported a naming disadvantage for all noun stimuli in PD compared to neurotypicals, irrespective of their manipulability level. Notably, the same study also reported impaired naming of all verbal stimuli in PD, suggesting a more generalised impairment. Given that Cotelli et al. screened participants for cognitive impairment, these deficits cannot be attributed to global cognitive decline. A comparison of demographic and clinical variables across the three noun-naming studies indicates that the sample in Cotelli et al. had a lower level of education, pointing to a possible relation between education and lexical access abilities, potentially through neuroprotective mechanisms. Other variables, such as age and motor symptoms severity (as measured through UPDRS-III), were comparable across studies and therefore unlikely to account for the observed naming differences.

Overall, findings on lexical access of verbs and nouns in PD speak in favour of a disadvantage associated with the condition. Picture naming performance for verbs in PD seems to be influenced by conceptual factors such as degree of motion and speed, properties tied to the encyclopaedic knowledge associated with verb roots rather than to semantic knowledge in the narrowly linguistic sense. To date, only one study has explained verb naming deficits in terms of syntactic properties related to argumental structure, raising the possibility that PD-related impairments in lexical semantics extend to interfaces with the language system. For nouns, some studies have identified a negative effect of the conceptual feature of manipulability in PD, a property that previous literature has typically operationalised in purely conceptual terms and that is not directly active within the language system.

Many researchers have envisioned the possibility of a link between the abnormalities in movement and motor control that are a hallmark of PD and the linguistic deficits observed in action semantics. This connection has prompted many researchers to propose that language-related processes are grounded in physical experiences. Such interpretations are in line with the framework of embodied cognition theories (Lakoff & Johnson, 1999; Barsalou, 1999, 2008), suggesting that physical experiences may also manifest linguistically through the mediation of the conceptual system. The central question, addressed in detail throughout this work, is whether PD-related interference is confined to the conceptual level or also affects aspects that are internal to, or interface with, the language system, such as argument structure, aspectual classifications, thematic role assignment, and *qualia* structure.

2.4.1 Embodied (Grounded) Cognition

When addressing lexical-semantic disturbances in PD, it is useful to situate empirical findings within a broader theoretical context concerning how conceptual knowledge is represented in the brain, and how lexical access relies on this representation. Within this perspective, the framework of embodied (or grounded) cognition offers valuable insights for interpreting selective lexical-semantic impairments observed in PD, while PD itself provides a natural test case for evaluating the predictions of this framework.

Embodied or grounded cognition theories (Lakoff & Johnson, 1999; Barsalou, 1999, 2008; Gibbs, 2005; Coello & Bartolo, 2012) posit that conceptual knowledge is partly constituted by the sensorimotor systems that support perception and action, through partial re-enactment or simulation of previous experiences during real-world interactions. Neuroimaging studies in neurotypical individuals, for example, have shown that understanding action-related words activates motor regions of the brain, suggesting a partial overlap between action execution and action representation (Hauk et al., 2004; see Kuhnke et al., 2023 for a meta-analysis). A substantial body of research shows that many conceptual features such as colour, shape, motion, and manipulation, are associated with activity in high-level perceptual and motor cortices that process those attributes (Binder & Desai, 2011). These modality-specific representations coexist with supramodal zones that support more abstract conceptual knowledge.

However, it is essential to distinguish conceptual representation from linguistic meaning. The claim of embodiment concerns with how concepts are neurally instantiated, and it does not entail that word meaning is sensorimotor in nature. Word meaning depends additionally on thematic structure, argument structure, aspectual properties, which belong to the interface between the conceptual system and morphosyntax, and are not reducible to perceptual-motor traits (cf. Mahon & Caramazza, 2008; Caramazza et al., 2014). Therefore, embodiment is best viewed as a theory of conceptual grounding, relevant to the lexicon because lexical items access concepts, but not a theory of the linguistic system itself.

Within the embodiment framework, three classes of theories can be distinguished: embodied or modality-specific theories, which posit that retrieving conceptual content requires the activation of sensorimotor circuits (Pulvermüller, 2005, 2013); amodal (“disembodied”) theories, which maintain that concepts are represented in an abstract, symbolic fashion, independent of modality (Fodor, 1975; Pylyshyn, 1984; Burgess & Lund, 2000); and hybrid accounts, which posit partially modality-specific conceptual features embedded within a broader supramodal system, including convergence zones such as the anterior temporal lobes (Binder & Desai, 2011; Caramazza et al., 2014). In this view, some conceptual features may be associated with modality-specific cortices, but the integration and organisation of conceptual knowledge rely on supramodal regions that dynamically interact with sensorimotor and linguistic systems.

Because strict accounts of embodiment (modality-specific theories) situate conceptual action knowledge within motor circuits, they predict that degeneration of the motor system should selectively compromise the conceptual features underlying verbs associated with high motion and nouns associated with high manipulability. Disruption of motor networks caused by PD could weaken the sensorimotor underpinnings of action-related concepts, leading to selective deficits in lexical retrieval (Fernandino et al., 2013a; Bocanegra et al., 2017). Another interpretation compatible with existing evidence is that access to action- and manipulation-related meaning is impaired, rather than its representation; this would equally account for the selective deficits in the retrieval of verbs and nouns encoding rich action or manipulation features. This possibility aligns with weaker formulations of embodiment which, while acknowledging activation of somatomotor grounding of conceptual knowledge, emphasise the morphosyntactic mechanisms that interact with conceptual processing during lexical access. To achieve a better understanding of lexical access in PD, integrating embodiment with models of lexical selection and control is therefore of crucial importance, in order to examine not only how conceptual knowledge is grounded and represented, but also how it is retrieved and integrated into the language system.

2.4.2 Models of Lexical Access, Selection, and Control

Lexical retrieval is widely understood as a multistage process that unfolds through a series of cognitive operations. The number and chronological unfolding of such operations has offered ample room for debate, with some accounts proposing a three-stage model, progressing from conceptual activation through lemma selection to lexeme level and phonological encoding (Roelofs, 1992; Bock & Levelt, 1994; Levelt, 1999). Others postulate a simplified two-stage model, limiting the operations to the selection of a semantically and syntactically specified lexical representation (conceptual representation level), and the selection of the corresponding lexical-phonological representation (lexeme level) (Caramazza, 1997). According to another influential model (Indefrey & Levelt, 2004), lexical access begins with conceptual preparation, followed by lexical selection, morphological and phonological encoding, and culminating in phonetic encoding and articulation. Subsequent research has refined these models by proposing accounts in which such cognitive operations are not serial but rather parallel or interactive. Some event-related potential (ERP) studies have also measured the time course of lexical access itself (Costa et al., 2009). In PD, lexical retrieval deficits may arise at the conceptual level (weak activation of action or manipulation features) or later in the retrieval cascade, for instance when competing lexical candidates must be resolved.

Two debates stand out in current research on lexical access. First, whether selection is competitive, with co-activated alternatives slowing retrieval, or non-competitive, with interference arising at post-lexical stages (Finkbeiner & Caramazza, 2006; De Zubicaray & Piai, 2019). Second, whether lexical control draws on domain-general executive functions or on task-specific control mechanisms tuned to the lexical system (Nozari & Novick, 2017).

Neuroimaging suggests a division of labour between left temporal regions (semantic-lexical activation) and left inferior frontal gyrus (selection and control), though findings vary across studies. These perspectives are crucial for interpreting the linguistic impairment patterns observed in PD and for understanding how conceptual-semantic or linguistic features may affect naming performance in this condition.

2.4.3 Insights on the Mental Lexicon from Aphasiology

Aphasia research provides a useful comparative lens for understanding lexical impairments in PD. In people with aphasia, dissociation phenomena between nouns and verbs have been observed. In most cases reported in the literature, there is a more pronounced impairment for verbs compared to nouns, albeit deficits in nouns over verbs have also been described (e.g., in anomic aphasia). The term dissociation refers to the – perhaps simplified – idea that after brain damage, a specific cognitive process "dissociates" from the others, enabling the observation of the functioning of that brain area and the subsequent creation of theoretical models for that cognitive process. Dissociations between nouns and verbs have often been interpreted as evidence for distinct storage systems, with lesions in temporal regions linked to noun deficits and lesions in frontal regions to verb deficits. However, the distinction is not always so clear-cut (Luzzatti et al., 2006). Alternative accounts emphasise that such dissociations can also emerge from more graded, feature-based representations (Bird et al., 2000; Black & Chiat, 2003), shaped by task demands such as imageability and argument structure (Bird et al., 2000; Crepaldi et al., 2006). These insights suggest caution against a strict "two lexicons" view, and instead point toward more dynamic, interactional models of the organisation of the lexicon.

The dissociations identified in some conditions have permitted studying word formation and morphology and have been particularly meaningful also in modelling the mental lexicon. For example, agrammatism, a condition which affects closed-class words and leaves open-class words unaffected, has suggested partially independent processing of lexical bases and affixes, thus informing morphological research. Similarly, studies on nominalisation in aphasia highlight how lexical retrieval interacts with argument structure and event representation. Zanini and colleagues (2010) showed that an Italian-speaking aphasic individual with stroke-induced damage in the left frontal lobe and with verb deficits had a facilitation effect in a task where he had to derive nominals from verbs when he could make use of argument structure information. In particular, the aphasic subject performed better with complex event nominals [+ thematic roles] (e.g., *la camminata* "the walking") than with result nominals [- thematic roles] (e.g., *il cammino*, "the walk"); with participial nominals (e.g., *la scoperta* "the discovery, lit. the discover-ED") compared to derived nominals (e.g., *l'invenzione* "the invention"); with nominals followed by a prepositional-phrase argument (e.g., *la raccolta di grano*, "the collection of cereals") compared to *infinito sostantivato* ("infinitival nominal") followed by a direct argument (e.g., *il raccogliere giochi*, "games' collecting, lit. the TO-collect games"); with singular nominals (e.g., *la promessa*, "the-SING promise") compared to plural nominals (e.g., *le promesse*, "the-PL promises"). These patterns led the authors to conclude that the individual showed better performance on nominalisations that preserved verbal argument structure, and poorer performance on nominalisations that no longer provide access to that structure. Knowledge of the argumental structure of the verbs was therefore partially retained, suggesting a complex dynamics internal to the linguistic system, which allowed the participant to rely on preserved verb-related information even in the nominal domain. In more recent work, Zanini and colleagues (2014) tested aphasic subjects' ability to perform a completion task that requested to derive the target nominalisation from a verb in context. Error patterns, which involved substitution phenomena, did not show argument complexity effects. On the contrary, in analysing productions of elicited nominalisations, Zanini and colleagues highlighted the importance of event structure and the crucial role of aspect and Aktionsart. Other studies involving a picture naming paradigm reported effects of argument complexity across both nouns and verbs (Collina et al., 2001). Argument complexity was found to play a fundamental role in patients' ability to name pictures regardless of grammatical class, as they made fewer errors when producing non-argumental verbs and nouns. These mixed results suggest that dissociations may reflect broader vulnerabilities in encoding predicate-argument relations, rather than categorical separation of nouns and verbs.

It should be reminded that a previous study by Byng & Black (1989) found that aphasic patients were not always able to realise predicate-argument structures properly during sentence production. This leaves open the possibility that the mixed results obtained in evaluating the effect of A-structure in the production of nouns and verbs might be grounded in an even more general deterioration affecting the aphasics' evaluation of A-structure requirements. In this view, the deficit would concern not only the implementation of predicate-argument structure in production, but deeper, internal components of linguistic knowledge itself.

Task design also plays a crucial role. Crepaldi and colleagues (2006) compared picture naming with a sentential retrieval task and found that apparent noun-verb dissociations in aphasia (verbs impaired) often disappeared once imageability was controlled, pointing to the importance of experimental context. Neuroimaging evidence also adds details to the picture. In an fMRI study where neurotypical participants named identical pictures for three different grammatical conditions, Infinitive Verb (e.g., *mangiare*, "to eat"), Inflected Verb (e.g., *mangia* "she/he eats"), and Action Noun (e.g., *mangiata*, "the eating"), Siri et al. (2008) did not find any verb-specific activation, suggesting that nouns and verbs are processed by a shared neural system. Converging evidence from more recent neuroimaging research also challenges the classical noun-verb dissociation proposed in early neuropsychological accounts. For instance, Alyahya et al. (2018) tested individuals with chronic post-stroke aphasia combining behavioural testing and neuroimaging, and found no systematic difference in production and comprehension performance between nouns and verbs. Instead, patterns of impairment were better explained by disruptions in distributed semantic and control networks rather than by damage to discrete noun- and verb-specific regions. Similarly, a comprehensive review by Vigliocco and colleagues (2011) concludes that differences between nouns and verbs are not related to neural segregation between these two grammatical classes, but rather to graded semantic, pragmatic, and distributional properties that differentiate nouns and verbs.

Taken together, aphasiology findings indicate that noun-verb dissociation should not be taken as proof of separate lexical stores. Instead, they may emerge from the interaction of lexical, semantic, and syntactic features under task-specific demands. This perspective is highly relevant for PD: the selective vulnerability of action verbs and manipulable nouns in this condition may not reflect distinct lexical compartments, but rather the increased processing demands of feature-rich, argumentally complex representations under conditions of possibly impaired control.

2.4.4 Verbal Fluency in Parkinson's Disease

Verbal fluency tasks require a rapid generation of category-specific words based on a phonemic cue (e.g., words beginning with F) or a semantic category (e.g., animals) within a limited amount of time, typically one minute. Such tasks are widely used to probe lexical access and the organisation of the mental lexicon. Successful performance relies on both the structure of lexical-semantic networks (supporting clustering of related items) and executive processes (supporting switching and monitoring).

In PD, fluency performance is consistently reduced across phonemic and semantic conditions, with severity influenced by disease stage, executive functions, and demographic factors (Obeso et al., 2012; Koerts et al., 2013). Deficits are often attributed to reduced flexibility in switching between clusters rather than to cluster size, highlighting a control-based component (Pettit et al., 2013). People with PD also tend to produce less systematic and more repetitive retrieval patterns (Tagini et al., 2021; Zhang et al., 2022), and in some cases lower-frequency or earlier-acquired words, thus reflecting abnormal spreading activation (Foster et al., 2008; Wagner et al., 2020).

Certain fluency variants reveal selective vulnerabilities. Action fluency, for example, requires verb retrieval, and is frequently impaired even when standard fluency is preserved (Signorini & Volpato, 2006; Rodrigues et al., 2015), while proper name fluency is disproportionately affected, consistent with its heavier reliance on executive search strategies (Fine et al., 2011).

Taken together, fluency evidence suggests that lexical retrieval in PD is disrupted not only by executive and motor constraints, but also by subtle changes in the organisation and accessibility of the mental lexicon. For this reason, fluency tasks can provide a sensitive clinical marker of cognitive and linguistic impairment in PD, as well as a valuable window into the dynamics of lexical access in PD.

2.4.5 Motor Factors are Insufficient to Explain Lexical-Semantic Deficits in Parkinson's Disease

A final point concerning the interpretation of lexical-semantic impairment in PD targets the extent to which these deficits may be attributed to motor or articulatory dysfunction rather than to disruptions within the linguistic system itself. Speech-related motor difficulties and dysarthria are frequent in PD, and they can, in principle, affect naming latency and/or the quality of the output. However, across the naming and fluency literature reviewed above, converging evidence indicates that articulatory deficits cannot account for the selective lexical patterns observed in PD. Studies on picture naming, for example, consistently report dissociations in which lexical items with high action-relatedness are disproportionately impaired relative to low action-relatedness items, despite equal articulatory demands. These findings demonstrate that the lexical-semantic disturbances cannot be reduced to motor artifacts. Instead, they point to disruptions in processes intrinsic to the lexical system, such as the access and integration of conceptual and linguistic features, which interact with executive and motor changes, but crucially are not determined by them. Maintaining this distinction is essential for the correct interpretation of the linguistic profile of PD and for identifying the areas of lexical-semantic processing most selectively affected by this condition.

2.5 Syntax in Parkinson's Disease

Evidence indicates that PD affects the comprehension of complex syntactic structures. In sentence-picture matching tasks, people with PD are less accurate than controls in interpreting relative clauses, passives, negation, and topicalised constructions (Bocanegra et al., 2015; Johari et al., 2019a; Terzi et al., 2005). Rather than reflecting difficulty in mapping linguistic material onto external referents, these impairments appear to stem from the increased syntactic dependency load of these constructions, such as the long-distance relation between a dislocated element like a Wh-operator (e.g., "What course [Wh-phrase] did the teacher say that he wants us to take _ [trace]?") or the head of a relative clause and its trace (e.g., "The boy [head] that Mary has invited _ [trace]"). Similar reasoning underlies classic work by Caramazza & Zurif (1976), who showed that comprehension can break down when successful interpretation depends on computing syntactic structure, even when semantic or referential information is available. In PD, this syntactic-computational vulnerability has been reported even in the absence of dementia.

Thematic role identification studies also converge in highlighting this vulnerability, with particular difficulty in object-relative clauses (Angwin et al., 2005; 2007). In grammaticality judgments, PD groups detect violations less reliably than controls (Johari et al., 2019a).

Tasks requiring semantic integration reveal similar patterns. Individuals with PD are slower and less accurate when judging the plausibility of sentences with action verbs, especially in figurative contexts (Fernandino et al., 2013b; Humphries et al., 2019). Narrative comprehension tasks show selective impairment in processing action-related information (García et al., 2018), although broader discourse organisation can remain intact (Ash et al., 2012).

Deficits also emerge in ambiguity resolution and anomaly detection. People with PD are more likely to access context-inappropriate meanings of ambiguous words (Angwin et al., 2017) and are less sensitive to semantic-syntactic mismatches (Whiting et al., 2005). In sentence completion paradigms, individuals with PD fail to exploit lexical frequency in predictive processing (Isaacs et al., 2021), though eye-tracking studies suggest that verb-based anticipatory mechanisms may remain intact (Aveni et al., 2023).

Overall, syntactic processing in PD is consistently impaired under conditions of high structural or semantic complexity. While some difficulties reflect reduced executive resources (e.g., working memory constraints), others point to a more specific weakening of syntactic-semantic integration mechanisms.

2.6 Pragmatics in Parkinson's Disease

Pragmatic aspects of language, which heavily rely on context and inference, are also compromised in PD. Speech act recognition is less efficient: while controls benefit from contextual cues in lexical decision tasks, people with PD do not (Holtgraves & McNamara, 2010).

Individuals with PD also show deficits in implicature processing, responding more slowly and less accurately when indirect meanings are required (McNamara et al., 2010). Broader inferential comprehension is affected, since explicit information in discourse is generally preserved, while implicit content is recalled less accurately (Monetta et al., 2008).

Complex pragmatic phenomena such as irony and metaphor are particularly vulnerable. PD participants are less accurate than controls in interpreting ironic statements (Monetta et al., 2009) and show reduced comprehension of metaphorical language, especially when working memory is taxed (Monetta & Pell, 2007).

Standardised pragmatic assessments confirm these deficits. Italian studies using the APACS battery report impairments in figurative language, humour, and narrative comprehension (Montemurro et al., 2019; Baraldi et al., 2021), while English studies with the TLC-E identify difficulties in inference and metaphor interpretation (McKinlay et al., 2009).

Taken together, the evidence indicates pervasive pragmatic impairments in PD, encompassing speech act recognition, implicatures, figurative language, and humour. While cognitive limitations contribute, the selective vulnerability of inferential and non-literal meaning suggests that pragmatic processing constitutes a distinct deficit in PD.

2.7 Summary and Conclusions

Language competence in PD is compromised across multiple domains. Hypokinetic dysarthria is highly prevalent and emerges early, providing a potential phonetic diagnostic marker. Deficits in phonological awareness and prosodic processing suggest impairment that goes beyond articulation. Inflectional and derivational morphological processes are vulnerable, particularly when inhibition of alternatives is required. Lexical retrieval is especially affected, with selective difficulties in action verbs and manipulable nouns. These deficits can be interpreted with reference to models of lexical access and control and informed by aphasiology, evidence from fluency tasks, and embodied cognition theories. In the syntactic domain, people with PD struggle with complex structures, thematic role assignment, and ambiguity resolution, reflecting an interaction between linguistic and executive constraints.

Difficulties extend to speech act recognition, implicatures, figurative language, humour, and irony, with working memory limitations exacerbating pragmatic impairments.

Overall, the evidence supports the view that PD entails heterogeneous linguistic deficits, shaped by interactions between motor, cognitive, and linguistic systems. Semantic competence stands out as a particularly informative domain, given its close ties to motor processing and its relevance for testing theories of lexical access and embodied cognition. This perspective, however, calls for a crucial distinction between conceptual-semantic processes that rely on domain-general mechanisms and those semantic processes that are intrinsic to the linguistic system itself. The following chapters will explore this central distinction and its theoretical implications.

Chapter 3 – Implicit Learning in Parkinson's Disease

This chapter reviews experimental evidence on implicit learning in PD. The rationale behind investigating implicit learning in PD lies in the fact that this disease compromises the basal ganglia and the circuits involving them, which coincide with those involved in processing procedural knowledge. The chapter begins with some conceptual clarifications and a historical overview of this construct, followed by a review of the literature focusing on implicit learning in PD operationalised across multiple paradigms. Because implicit learning itself is a heterogeneous notion, a terminological section will clarify its main subtypes. Given that PD significantly affects movement, special attention will be paid to distinguishing between tasks presenting motor output demands on behalf of the participants and tasks that minimise them, in order to control for motor confounds in interpretation. Additionally, information on the clinical characteristics of the participants will be reported whenever available, including their cognitive status and their treatment state, such as dopaminergic medication, deep brain stimulation (DBS), and transcranial direct current stimulation (tDCS). The aim is to situate implicit learning within the broader cognitive and linguistic profile of PD, extending the clinical and linguistic perspectives covered in Chapters 1 and 2.

3.1 Defining Implicit Learning

Implicit learning can be defined as incidental acquisition of knowledge, without conscious awareness on behalf of the learner. Studies on implicit learning are historically rooted in the work by Reber (1967), who designed experiments intended to resemble aspects of language acquisition. In this work, which paved the way to the investigation of the ability to unconsciously acquire rules from the input, participants were exposed to strings of letters generated either according to a finite-state grammar or at random. Participants in the grammar condition exhibited sensitivity to the rules underlying the stimuli, which was evident from their more efficient learning, presumably driven by the grammatical organisation of the materials. Crucially, subjects did not show any awareness of those rules, knowledge of which remained therefore implicit.

Reber's findings were preceded by the influential research conducted by Gibson and Gibson (1955) on perceptual learning, described as the increased specificity of responses to complex stimuli through repeated exposure. Reber's contribution indicated that the Gibsonian method of repeated exposure to stimuli variation could apply not only to perceptual learning in the visual domain but also to implicit learning of an artificial language, in which the stimuli were organised according to a finite-state grammar. Parallel to these developments, George Miller and colleagues explored the role of organisation and redundancy in memory. Miller's studies on free recall, including his "Project Grammarama" showed that redundant strings of letters obtained through a finite-state generator were learnt more quickly than random control strings. Moreover, the amount of information remembered was bigger in terms of single letters, as chunking strategies allowed to recode information reducing processing demands (Miller, 1958; 1967). In the terminology of Aborn and Rubenstein (1952), the forerunners in studying the effect of rules in memorisation tasks, participants were able to learn more symbols but less information, as a higher degree of organisation would determine an overall facilitation effect in performing a memory-based task.

These early contributions by Reber and Miller opened two partially overlapping streams of research over time: one focusing on implicit learning, which generally involved the Artificial Grammar Learning (AGL) methodology, and later incorporated probability learning and serial-reaction time (SRT) tasks, aimed at assessing the cognitive mechanisms involved during learning itself; the other focusing more on what structures could be learned, and being therefore closer to the domains of linguistics and psycholinguistics. Over time, the terminological landscape grew increasingly complex, with some researchers using "implicit learning" to denote a wide array of phenomena, while others preferred the label "statistical learning" to emphasise the sensitivity to distributional properties of the input (Conway and Christiansen, 2006; Christiansen, 2019). Various attempts have been made to reconcile the several approaches, sometimes referring to this heterogeneous domain with the term "implicit statistical learning" (Christiansen, 2019; Arnon, 2019). Despite later divergences, the starting point was unique: the observation that humans (and not only) can extract regularities from experience incidentally and are able to exploit this information in ways that reveal that such underlying knowledge exists.

3.1.1 Terminological Distinctions

Clarifying terminology is particularly important in the context of PD, as different paradigms are differentially sensitive to the neural circuits affected by the disease (Tsay et al., 2022), in particular basal ganglia and cortico-striato-thalamo-cortical loops (Parent & Hazrati, 1995), which are affected by the PD pathology (Galvan et al., 2015).

Although *implicit learning* is often used as an umbrella term, the literature distinguishes several constructs, a few of which will be named hereafter, each of which putting the emphasis on slightly different aspects. *Statistical learning* refers to the incidental extraction of distributional patterns, such as transitional probabilities from sensory input, without explicit instruction. This type of learning may recruit regions outside of the basal ganglia, such as temporal and parietal cortices (Cunillera et al., 2009). However, a broadly accepted definition of statistical learning remains elusive, ranging from more narrow definitions to the claim that "all learning is statistical learning" (see also Frost et al., 2019).

Procedural learning emphasises the gradual acquisition of skills and habits through practice and feedback, processes that are strongly associated with cortico-striato-thalamo-cortical loops and heavily rely on striatal dopamine-dependent mechanisms (Muslimović et al., 2007). A related but distinct tradition is that of feedback-based *probabilistic learning*, exemplified by the Weather

Prediction task, in which participants gradually acquire category knowledge based on trial-by-trial reinforcement (Li et al., 2016).

An additional domain is that of *sensorimotor adaptation*, which focuses on error-driven recalibrations, for instance in visuomotor rotation or force-field adaptation, where learning is inferred from automatic corrective adjustments. This form of learning engages cerebellar as well as striatal contributions (Seidler, 2010). Finally, the term *motor learning* generally refers to a process that aims at the optimisation and automatisation of motor skills, and generally includes both implicit and explicit components (Marinelli et al, 2017). Motor skill acquisition neurally involves a cortico-striatal network including the caudate and putamen, which is dynamically recruited during learning phases, along with the supplementary motor area (SMA) and the primary motor cortex (M1), and modulated by nigro-striatal dopaminergic neurotransmission directed to the posterior sensorimotor putamen (Muehlberg et al., 2024).

3.2 Reviewing the Literature on Implicit Learning in Parkinson's Disease

The heterogeneity of implicit learning mechanisms helps explaining why findings on these skills in PD are not uniform across tasks. Deficits may arise in studies and tasks taxing striatal circuits more heavily, and be less evident when a more distributed cortical, cerebellar contribution is in place. Research into implicit learning in people with PD began in the early '90s and since then it has developed into a heterogeneous field presenting the entire rich array of paradigms that were available from previous research on healthy individuals. In particular, it spans from implicit sequence learning (Serial Reaction Time paradigm with motor and perceptual variants) to artificial grammar learning, and probabilistic learning (weather prediction). In the context of PD, several moderating variables must be taken into account when interpreting implicit learning results, for example treatment state (ON or OFF dopaminergic medication, DBS ON or OFF, stimulation parameters in tDCS), clinical phenotype, cognitive and affective status. The interaction between these factors and task design can substantially impact performance outcomes.

3.2.1 Implicit Sequence Learning

The most frequently employed paradigm in this area is the Serial Reaction Time (SRT) task, in which participants are asked to respond to stimuli appearing in a sequence, typically by pressing a key or a button corresponding to each stimulus. Early studies suggested that people with PD were able to acquire basic sequential regularities when motor confounds were minimised, showing learning curves comparable to those of neurotypical controls (Westwater et al., 1998; Smith et al., 2001). However, later work revealed a more complex picture. When tasks required the integration of higher-order transitions or imposed dual-tasks demands, individuals with PD showed reduced sequence learning and diminished retention effects (Smith et al., 2006; Seidler et al., 2007). Experimental studies (Vandenbossche et al., 2009; Gobel et al., 2013) and meta-analyses (Siegert et al., 2006) converge on the conclusion that implicit sequence learning in PD is highly heterogeneous, with outcomes determined by task complexity, methodological choices, and participants' cognitive status, with MCI participants more likely to show deficits compared to people without cognitive decline.

A particularly evident factor concerning SRT is that this type of tasks involves the necessity to provide a motor response. In the studies that identify a deficit in implicit learning in PD when an SRT task is used, it is not clear how to disentangle the cognitive impairment from the motor impairment intrinsically associated with the condition. In this context, perceptual variants of sequence learning tasks have been particularly informative in clarifying the role of motor execution. When learning is probed through perceptual judgments rather than motor responses, people with PD exhibit preserved sequence sensitivity (Firouzi et al., 2021). These findings underscore the importance of separating learning processes from the motor demands of the response used to assess them. Other implicit learning paradigms with reduced motor requirements like contextual cueing (van Asselen et al., 2009) and dynamic system control (Witt et al., 2006) also point to relative preservation of learning in PD. The implication is that PD does not completely impair the capacity for implicit sequence acquisition *per se*, but rather constraints it when the task requires rapid integration of complex regularities under motor or cognitive load.

3.2.2 Artificial Grammar Learning

Artificial grammar learning (AGL) tasks offer another window into implicit learning, with the advantage of minimising motor output and instead focusing on the detection of structural regularities in symbolic sequences. Several studies have demonstrated that individuals with PD perform comparably to controls in classifying grammatical versus non-grammatical strings, even at more advanced disease stages (Peigneux et al., 1999; Witt et al., 2002).

These results suggest that the ability to extract rule-like patterns from exposure remains relatively intact, in contrast with the difficulties sometimes observed in motor-based sequence learning.

3.2.3 Probabilistic and Feedback-Based Learning

Another stream of research has focused on probabilistic classification tasks, of which the Weather Prediction paradigm is the best known. In these tasks, participants are asked to classify stimuli based on probabilistic cue-outcome contingencies, receiving trial-by-trial feedback. Such tasks have been widely interpreted as involving striatal reinforcement learning mechanisms. In PD, performance is often impaired, with participants showing slower or noisier acquisition of the underlying regularities (Sage et al., 2003).

Functional studies have confirmed that the striatum is crucially engaged during these tasks and that its dysfunction contributes to the observed deficits (Holl et al., 2012). Moreover, surgical and stimulation interventions can modulate performance. For example, pallidotomy was shown to alter probabilistic learning outcomes (Sage et al., 2003) and subthalamic DBS produced changes in acquisition curves (Wilkinson et al., 2009). These findings support the idea that feedback-based implicit learning is selectively vulnerable in PD, and its integrity is strongly dependent on the dopaminergic status of cortico-striatal loops.

3.2.4 Effects of Dopaminergic Medication and Neuromodulation on Implicit Learning in PD

The effects of dopaminergic medication on implicit learning are complex and task dependent. Some studies suggest that a single dose of levodopa can modulate implicit learning in drug-naïve people with PD, particularly in the early stages of the disease (Geffe et al., 2016). Other studies, however, report null effects (Paul et al., 2018) or interactions that depend on the type of learning required (Marzinzik et al., 2011; Perugini et al., 2016, 2018). A growing consensus is that these findings result from the so-called "dopamine overdose" hypothesis, according to which medication may restore functioning of dopamine-depleted circuits while simultaneously impairing relatively impact ones (Brooks, 2006). This perspective explains why dopaminergic treatment may facilitate certain implicit tasks while disrupting others.

As far as other treatment types are concerned, pallidotomy and DBS can alter probabilistic classification learning (Sage et al., 2003; Wilkinson et al., 2011), while expectancy effects and placebo/nocebo responses have also been documented (Keitel et al., 2013). Non-invasive stimulation techniques such as transcranial direct current stimulation (tDCS) have also been applied to implicit sequence learning, with promising but still variable results. In particular, Firouzi and colleagues (2021, 2024) reported that stimulation on the motor cortex improved sequence learning in PD participants with MCI, suggesting that neuromodulation may enhance residual learning capacities when cognitive status is compromised. However, outcomes depend on stimulation montage, disease profile, and task, thus not yet allowing broader generalisations.

3.2.5 Compensatory Processes for Implicit Learning in PD

Visuomotor learning studies highlight contributions not only of the striatum but also of the cerebellum and frontal regions, suggesting that individuals with PD may recruit alternative circuits to support performance (Doyon et al., 1997; Marinelli et al., 2017). Other neuroimaging studies have found evidence of medial temporal lobe activation during implicit learning tasks (Moody et al., 2004; Beauchamp et al., 2003), supporting the interpretation that compensatory cortical mechanisms can sustain learning when striatal loops are impaired.

3.3 Evidence from Neighbouring Pathologies

Some studies have dealt with implicit learning in parkinsonian syndromes other than PD. Sommer and colleagues (2001) found that eyeblink conditioning, which heavily relies on cerebellar circuits, was impaired in individuals with progressive supranuclear palsy (PSP) but not in PD. Similarly, people with multiple system atrophy (MSA) showed impairment in eyeblink conditioning and in a SRT task compared to individuals with PD (von Lewinski et al., 2013), pointing to distinct pathophysiological signatures of basal ganglia degeneration (PD) compared to brainstem degeneration (PSP), or combined basal ganglia, cerebellar, and autonomic impairment (MSA).

3.4 Summary and Conclusions

Three decades of research indicate that implicit learning in PD has revealed heterogeneous results, which depend on the required computations. Sequence learning is relatively preserved when motor demands are low, while it is compromised when experimental conditions require higher-order integration. Artificial grammar learning remains intact, speaking in favour of a retained sensitivity to abstract structure, while probabilistic classification shows consistent vulnerability, reflecting the dependence of feedback-based learning on striatal processes and dopamine. Dopaminergic therapy and neuromodulation can both facilitate and disrupt implicit learning depending on the circuit and paradigm engaged during the task. Several studies highlight compensatory recruitment of cortical and medial temporal structures, which may sustain learning when striatal loops are compromised. This heterogeneous account highlights that it is of paramount importance to employ precise terminology concerning tasks and requirements, as well as a detailed reporting of treatment and clinical state in order to correctly interpret implicit learning in PD.

Chapter 4 – Open Research Questions and Our Studies

This chapter builds on the clinical, linguistic, and cognitive background laid out in the previous chapters, and identifies specific gaps and open research questions that motivated the experimental studies presented in Part II.

4.1 Study 1: Lexical Access and Semantic Competence in Parkinson's Disease

Prior work shows that people with PD display linguistic deficits across multiple domains, with growing evidence pointing to impairments in lexical semantics. Impairments in lexical retrieval, defined as the process of getting from a concept to a spoken word, have been observed in a series of tasks, among others in picture naming, an experimental paradigm in which subjects are presented with a picture and are asked to quickly and accurately produce the corresponding word. Behavioural accuracy findings indicate selective deficits for high-motion verbs, e.g., "to dance", compared to low-motion verbs, e.g., "to read" (Herrera et al., 2012; Bocanegra et al., 2017; for a more detailed account, refer to Chapter 2). However, alternative accounts attribute verb naming deficit to syntactic complexity and argument structure rather than semantics *per se* (Aiello et al., 2022a).

In the nominal domain, naming performance appears sensitive to manipulability, with high-manipulability nouns, e.g., "screwdriver", being more difficult to retrieve relative to low-manipulability nouns, e.g., "mountain" (Bocanegra et al., 2017; Johari et al., 2019a), though some studies report a broader noun-naming impairment not modulated by semantic features (Cotelli et al., 2007).

To unify verbal motion and nominal manipulability under a single motion-related construct, we adopt the term *action-relatedness* from now on. As an additional terminological note, Aiello et al. (2022a) also attempted to subsume verbal motion and nominal manipulability under a single label, using the term *actionality*. It is worth clarifying, however, that within the linguistic tradition *actionality* (Italian: *azionalità*) has a more established and specific meaning: it denotes the semantic classification of eventuality types, originally formulated by Vendler (1957) into states, activities, accomplishments, and achievements, and further developed in later work (e.g., Bertinetto, 1986). Crucially, this notion concerns the internal temporal properties of events and is typically treated as an intra-linguistic semantic category rather than a broader sensorimotor or extra-linguistic construct. To avoid potential terminological ambiguity, we therefore adopt *action-relatedness* as an umbrella term.

A key unresolved issue is where in the lexical retrieval cascade PD-related deficits arise. The following two non-exclusive loci represent plausible targets:

1) Conceptual-semantic locus: the sensorimotor/action features are degraded at the level of conceptual representation and reduce conceptual activation for items with high action-relatedness. This view is consistent with strict embodied cognition views;

2) Linguistic locus: features that are encoded within the language system, e.g., argument structure, agentivity, telicity, and *qualia* structure, modulate processes of selection and control, and their impairment therefore affects efficient retrieval.

In light of the above, and with the aim of assessing whether naming deficits in PD reflect conceptual action-relatedness, linguistic structure, or their interaction, Study 1 hinges on the following research questions:

(1) Is picture naming performance for nouns and verbs impaired in PD compared to healthy matched controls?
(2) How do conceptual (action-relatedness-driven) and linguistic (structure-driven) features interact in shaping naming performance in PD and control individuals?
(3) Does action-relatedness (encompassing motion for verbs and manipulability/implied motion for nouns) modulate naming performance differently in PD and controls?
(4) Do language-specific characteristics, such as argument structure and agentivity for verbs and *qualia* structure and telicity for nouns account for additional variance in naming beyond action-relatedness?

If impairment emerges merely in conceptual semantics showing robust action-relatedness effects, lexical retrieval deficits in PD may arise directly at the conceptual level of the cascade from degraded sensorimotor representations. Alternatively, if linguistic features (argument structure, agentivity, *qualia* structure, and telicity) modulate lexical access performance with independent effects, disruptions may occur also at the level of the language system when accessing linguistic features. Interactions between the conceptual and linguistic dimensions might also be present.

4.2 Study 2: Morphological Competence in Parkinson's Disease

A persistent limitation in the PD literature comparing naming performance of verbs and nouns is that the choice of stimuli often falls on event-denoting items for verbs and object-denoting items for nouns. This choice conflates conceptual semantics with syntactic category, making it impossible to disentangle the two components, resulting in a diminished explanatory power on the nature of the deficit itself, leaving open the possibility for a more precise attribution.

We address this by leveraging deverbal nominals, which represent a valid tool to address this issue more neatly, as they syntactically behave as nouns while encoding event (verb-like) semantics. Their peculiar hybrid status allows a cleaner test for phenomena that hinge on the separation between nouns and verbs, such as noun-verb dissociation phenomena reported in the clinical literature. Deverbal nominals can come with a varying degree of morphological complexity, and this should also be considered when testing whether the bottleneck is conceptual or linguistic.

Study 2 is therefore based on the following research questions:

(1) Does syntactic category (nouns vs. verbs) and action-relatedness (high vs. low) modulate naming performance in PD?
(2) Does morphological complexity affect naming capacities in PD beyond semantic content?

If both nouns and verbs show impaired retrieval specific for concepts with high action-relatedness, this would indicate that PD disrupts access to the conceptual feature of action-relatedness regardless of the syntactic or morphological category through which these concepts are expressed. In this case, the deficit originates in the conceptual system (conceptual locus), not in its linguistic implementation. If specific morphosyntactic categories show impairment independently of action-relatedness, this would support a linguistic-level impairment tied to syntactic or morphological encoding (linguistic locus). If impairment emerges selectively for items with high action-relatedness only when they are encoded in specific morphosyntactic structures (e.g., complex event nominals), this would suggest that accessing this conceptual feature is not intrinsically difficult. Rather, difficulties arise only when features must be expressed through specific linguistic categories. This pattern would indicate that lexical retrieval in PD is compromised at multiple levels, with deficits becoming evident only when the conceptual action feature is linguistically mediated.

4.3 Study 3: Implicit Learning with Minimal Motor Demands

Moving on to our second cognitive dimension of interest, implicit learning in PD, previous literature has revealed heterogeneous results (Chapter 3), largely depending on task demands. Sequence learning can be reduced by motor or task complexity demands, whereas artificial grammar learning often remains intact. To isolate learning from motor execution, in addition to a more traditional SRT task, we use an eye-tracking paradigm featuring a rotating design (reducing the alternation bias) and a Fibonacci artificial grammar to distinguish between different types of regularities (details in Chapter 8). Our research questions were the following:

(1) Do individuals with PD and control participants implicitly acquire the transitional regularities underlying a sequence of visually presented stimuli?
(2) Do their motor responses throughout the task reflect learning?
(3) Do they perform anticipatory eye movements towards the target visual area, thereby demonstrating learning through predictions of the upcoming stimuli?

In our design (see Chapter 5), behavioural performance in the SRT task serves as a proxy for implicit learning of the presented sequence, although the motor demands of the response may tax PD individuals more than controls, thereby masking learning-related effects in the clinical population. To minimise motor confounds, we complemented the SRT task with an eye-tracking paradigm in which learning is probed through online anticipatory oculomotor behaviour. Anticipatory fixations require a minimal motor output, reducing the ambiguity that arises in interpreting results when impaired motor execution and impaired acquisition are conflated.

Moreover, this paradigm allows us to probe regularities associated with a different level of complexity. Crucially, the occurrence of the predicted stimulus after each anticipatory movement provides an implicit form of trial-by-trial feedback, linking our task to feedback-based probabilistic learning paradigms.

If PD participants show intact oculomotor anticipatory behaviour, this would align with evidence of preserved implicit learning and sensitivity to structure. Conversely, if sensitivity to the regularities is reduced, this would strengthen the view that striatal dysfunction undermines reinforcement-based implicit learning. If performance is preserved in all conditions, this would suggest the recruitment of compensatory mechanisms beyond the striatum.

4.4 Cross-Cutting Questions

Our design, including PD and matched controls (HCM), along with a younger control group (HCY) which will allow future ageing-related investigations, enables formulating overarching research questions. In particular, aside from the specific questions formulated above, our work also informs broader topics:

(1) What is the relation between language processing and domain-general mechanisms, such as implicit learning, in the healthy and pathological brain?
(2) Are linguistic impairments in PD associated with right-sided motor symptomatology, which compromises the contralateral left hemisphere, typically dominant for language?
(3) Is there a link between motor dysfunction and linguistic performance in PD, and does the latter correlate with motor severity scores?
(4) What is the role of subcortical structures (e.g., basal ganglia) in processing language?
(5) What is the role of dopamine in modulating linguistic and cognitive functions?
(6) What insights does the PD population provide on theories on grounded cognition?

Taken together, these questions highlight the broader significance of our work. Ultimately, by targeting non-motor aspects of PD such as language competence and implicit learning, this work seeks to identify early cognitive-linguistic markers of the disease. In doing so, the project aims at accelerating

PD detection by informing diagnostic practices, and contributing to a deeper understanding of the pre-motor stages of the condition before overt motor decline.

PART II – EXPERIMENTAL STUDIES

Part II presents the experimental studies that constitute the empirical core of this dissertation. Building on the theoretical groundwork laid in Part I, these studies investigate how individuals with PD perform in tasks involving lexical access and derivational morphology, with a specific focus on the interaction between conceptual features (such as action-relatedness) and linguistic features (such as argument structure and *qualia* structure). A second domain of investigation concerns implicit learning skills, also explored in relation to the interplay between domain-specific language mechanisms and domain-general implicit learning processes in both healthy and pathological conditions. The overarching aim is to determine whether and how these dimensions reveal differences between individuals with PD and neurotypical participants. In doing so, this work seeks to provide novel insights into the nature of language and cognitive deficits in PD, as well as potential tools to inform diagnostic practices.

The chapters unfold as follows: Chapter 5 details the methodological framework, including experimental procedures, participants, and assessments. Study 1, focusing on lexical access and semantic competence, is presented in Chapter 6. Study 2, on deverbal nominals and the disentangling of conceptual and linguistic contributions, is presented in Chapter 7. Study 3, employing an eye-tracking-based implicit learning paradigm, is discussed in Chapter 8. A complete discussion of all findings will then be offered in Part III.

Chapter 5 – General Methods: Overall Study Design and Participants

5.1 Overall Study Design and Experimental Pipeline

In this chapter we present an overview of the entire experimental programme comprising Studies 1–3, which will be examined in detail in the next chapters. The studies aimed to assess language competence and implicit learning skills in a group of people diagnosed with PD and in a group of healthy control individuals (HCM) matched to the experimental sample on key demographic variables. The experimental pipeline comprised two separate sessions for each subject and lasted approximately 60-90 minutes each (Table 1).

During the first sessions, all participants underwent a full neuropsychological evaluation encompassing measures of executive functioning (Frontal Assessment Battery, FAB), global cognitive status (Montreal Cognitive Assessment, MoCA), and affective state, including anxiety and depression (Hospital Anxiety and Depression Scale, HADS). Then, they completed a computer-based picture naming task allowing to evaluate their lexical access capacities (Study 1) and an elicited production task to assess their morphological capacities in relation to lexical retrieval (Study 2). Finally, a questionnaire was employed to collect additional sociodemographic information (age, sex, years of education), as well as data on language-use habits (including foreign languages and dialects), handedness, and meal preparation habits.

The second session began with an additional assessment of executive functioning and set-shifting using a novel eye-tracking-based Trail Making Test (TMT), Parts A and B, followed by an eye-tracking-based implicit learning protocol implemented as a modified Serial Reaction Time (SRT) Task featuring visual stimuli arranged according to the Fibonacci artificial grammar (Study 3).

All participants completed the same experimental pipeline regardless of group membership. In addition, individuals belonging to the PD group received a neurological examination by the same neurologist, in order to characterise disease severity and functional impairment by means of the Unified Parkinson's Disease Rating Scale (UPDRS). This examination was typically conducted at the beginning or end of the second session, depending on logistical constraints.

Table 1. Pipeline of the Experimental Procedure

Tasks and activities	**Session 1**	**Session 2**
1.1 **Neuropsychological evaluation** • FAB (executive functions) • MoCA (cognitive screening) • HADS (anxiety and depression)	X	
1.2 **Picture naming** protocol involving both verbs and nouns	X	
1.3 **Elicited production** task (morphological derivation and base retrieval)	X	
1.4 **Questionnaire** (socio-demographic, handedness, linguistic information)	X	
2.1 Eye-tracker-based **TMT (A + B)** for executive functions		X
2.2 **Implicit learning** protocol		X
2.3 **Neurological exam** on the Unified Parkinson's Disease Rating Scale (UPDRS)		X

Note. FAB = Frontal Assessment Battery; MoCA = Montreal Cognitive Assessment; HADS = Hospital Anxiety and Depression Scale; TMT = Trail Making Test.

5.2 Overview of Studies 1–3

This section provides an overview of the goals and tasks involved in each study (see also Table 2). Study 1 focuses on the domain of lexical semantics in PD by means of a picture naming task. Building on the open research questions highlighted in Chapter 4, the study aims to disentangle the relative contribution of conceptual and linguistic features to naming performance, in order to determine whether PD-related deficits have a primarily conceptual or linguistic locus. To this end, the crucial dimensions of our stimuli were systematically manipulated. In particular, the stimuli were divided into two tasks featuring nouns and verbs separately. All stimuli were evaluated by a group of independent raters to collect their action-relatedness score, a measure tapping conceptual properties. Nouns were divided into seven linguistic classes based on their *qualia* structure and telicity: (1) tools, (2) ready-to-eat food, (3) food requiring a manual action, (4) food requiring a tool action, (5) artefacts, (6) shapes, and (7) natural objects. Verbs were grouped according to their argumental structure and agentivity into (1) unergative, (2) unergative with internal agentivity, (3) transitive achievements, (4) transitive accomplishments, and (5) unaccusatives. This protocol enabled us to assess the role of conceptual action-relatedness, linguistic structure, and their interaction in lexical access in PD.

Study 2 investigates the role of morphological competence in PD in the context of lexical retrieval. It employs two elicited production tasks in which participants read and listen to an elicitation sentence containing a prime, then use that prime to derive the morphologically corresponding form. In the first task, they had to derive either a coradical deverbal nominal or its base verb, with a 2 x 2 factorial design manipulating action-relatedness and part of speech. In the second task, the same elicitation procedure is used, but participants had to produce either a deverbal nominal or a morphologically simple noun, allowing the manipulation of morphological complexity. Overall, this study aims to disentangle conceptual variables (action-relatedness and encyclopaedic knowledge) from linguistic features, in this case morphosyntactic in nature, in order to evaluate their respective effects on elicited production performance and their potential deterioration in PD.

Study 3 focuses on implicit learning skills as measured through a modified Serial Reaction Time (SRT) Task featuring visual stimuli arranged according to the Fibonacci artificial grammar, combined with an online eye-tracking paradigm allowing to collect gaze behaviour throughout the task. This design allows us to collect both motor-mediated and eye-movement-based measures. While motor responses are recorded at stimulus onset, eye-movement predictions are measured in the time window preceding stimulus onset, thereby providing indices of both reactive and predictive processes.

All studies (1–3) drew from the same pool of participants described below.

Table 2. Overview of the Studies

Study	Objectives	Tasks / Measures
Study 1 – Lexical Access and Semantic Competence in PD	Investigate whether lexical access deficits in PD primarily reflect impairment in conceptual (action-relatedness) or linguistic (argument structure, qualia structure) dimensions; assess the interaction between conceptual and linguistic features in naming.	Picture naming task with verbs and nouns. Stimuli manipulated for: • Conceptual: action-relatedness ratings collected via raters; • Nouns: seven qualia/telicity-based classes (tools, ready-to-eat food, food requiring manual action, food requiring tool action, artefacts, shapes, natural objects); • Verbs: grouped by argument structure and agentivity (unergatives, unergatives with internal agentivity, transitive achievements, transitive accomplishments, unaccusatives)
Study 2 – Morphological Competence in PD	Determine whether PD-related impairments in lexical retrieval have a conceptual or morphosyntactic locus; disentangle effects of action-relatedness, morphosyntactic features (including morphological complexity) in morphological derivation task	Two elicited-production tasks: • Task 1: 2x2 manipulation of action-relatedness x part of speech (using primes to derive deverbal nominals or verbs); • Task 2: elicitation of noun stimuli with manipulation of morphological complexity (morphologically complex deverbal nominals vs simple forms), using the same prime-derivation procedure
Study 3 – Eye-Tracking-Based Implicit Learning in PD	Assess implicit learning in PD, distinguishing motor-mediated and predictive (eye-movement-based) indices of learning processes; evaluate learning of visual stimuli arranged according to the rules of an artificial grammar	Modified Serial Reaction Time (SRT) Task with visual stimuli arranged according to the Fibonacci artificial grammar, combined with continuous eye-tracking: • Motor responses at stimulus onset; • Eye-movement predictions measured before stimulus onset (anticipatory fixations)

5.3 Description of Participant Groups

Thirty-one individuals with PD, 34 matched healthy controls (HCM), and 32 younger healthy controls (HCY) participated in the three experimental studies presented in the following chapters. Although the subsequent chapters primarily focus on comparisons between the PD and HCM groups, reflecting the central aim of this dissertation, the demographic and neuropsychological profiles of the HCY participants will also be reported. Including this younger cohort opens avenues for future work examining how the measures investigated here evolve across the trajectory of healthy ageing. All participants were native Italian speakers.

The PD group consisted of individuals who had received a formal diagnosis of idiopathic PD from their neurologist and disease severity was determined by means of the Unified Parkinson's Disease Rating Scale (UPDRS). Neurological evaluation and both testing sessions were conducted during participants' "OFF" phase of antiparkinsonian medication. As discussed in Chapter 1, PD is a heterogeneous condition encompassing several parkinsonian syndromes that, despite overlapping clinical features, differ in underlying pathology. Here, the term "PD" refers exclusively to PD of the idiopathic type.

The PD and HCM groups were matched on key demographic variables, including age, education, biological sex, and handedness. Comprehensive demographic details and statistical comparisons between these groups are presented in Table 3.

The present study was approved by the Ethics Research Committee "Comitato Etico Territoriale Area Sud Ovest Veneto" (Prot. n. 21033, 08/04/2024) and conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013). All participants provided written informed consent.

5.3.1 Demographic Details

Due to our matching procedure, no significant differences were expected between the PD and HCM groups on demographic variables. Between-group comparisons were performed on participants' demographic details (Tables 3 and 4).

Table 3. Demographic Data (PD vs. HCM)

Demographic variables	PD ($N = 31$)	HCM ($N = 34$)	p-value
Age (years)	65.03 (6.66)	64.03 (8.23)	0.590
Education (years)	11.87 (3.30)	13.35 (3.65)	0.076
Biological Sex (F:M)	7:24	11:23	0.547
Handedness (R:L:A)	26:3:2	31:2:1	0.659

Table 4. Demographic Data (HCM vs. HCY)

Demographic variables	HCM ($N = 34$)	HCY ($N = 32$)	p-value
Age (years)	64.03 (8.23)	26.91 (3.75)	< 0.001
Education (years)	13.35 (3.65)	16.44 (2.35)	< 0.001
Biological Sex (F:M)	11:23	8:24	0.699
Handedness (R:L:A)	31:2:1	28:4:0	0.415

Note. PD = people with Parkinson's disease; HCM = matched healthy controls; HCY = younger healthy controls; F = female; M = male; R = right-handed; L = left-handed; A = ambidextrous.

Normality of the continuous variables (age and education) was assessed using the Shapiro-Wilk test. Age was normally distributed across all groups and therefore compared using two-tailed independent-samples *t*-tests. No significant difference was found between PD and HCM (PD: $M = 65.03$, $SD = 6.66$; HCM: $M = 64.03$, $SD = 8.23$; $p = 0.590$). As expected, participants in the HCM group were significantly older than those in the HCY group (HCM: $M = 64.03$, $SD = 8.23$; HCY: $M = 26.91$, $SD = 3.75$; $p < 0.001$; see Figure 1).

Education was not normally distributed in any of the three groups, as values tended to cluster around typical Italian schooling stages (such as completion of primary, middle, or high school, or university). Consequently, non-parametric Wilcoxon rank-sum (Mann-Whitney *U*) tests were used for group comparisons. No significant difference in years of education was found between PD and HCM (PD: $M = 11.87$, $SD = 3.30$; HCM: $M = 13.35$, $SD = 3.65$; $p = .076$), although a trend toward higher education was observed in the HCM group. In contrast, HCY participants displayed significantly higher education levels compared to HCM (HCM: $M = 13.35$, $SD = 3.65$; HCY: $M = 16.44$, $SD = 2.35$; $p < .001$; see Figure 2).

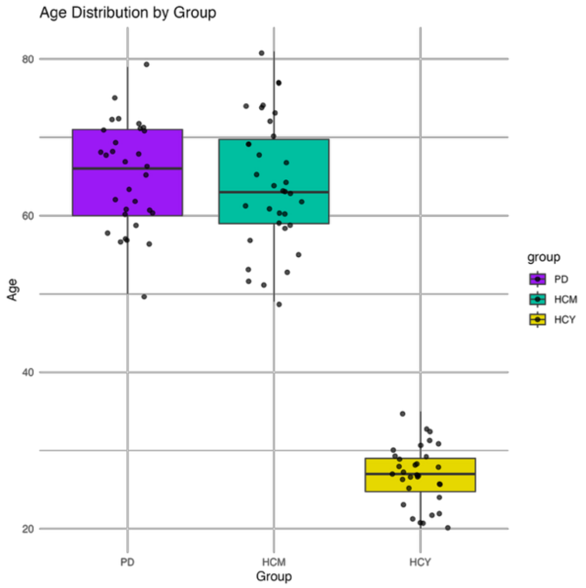


Figure 1. Distribution of Age across Groups

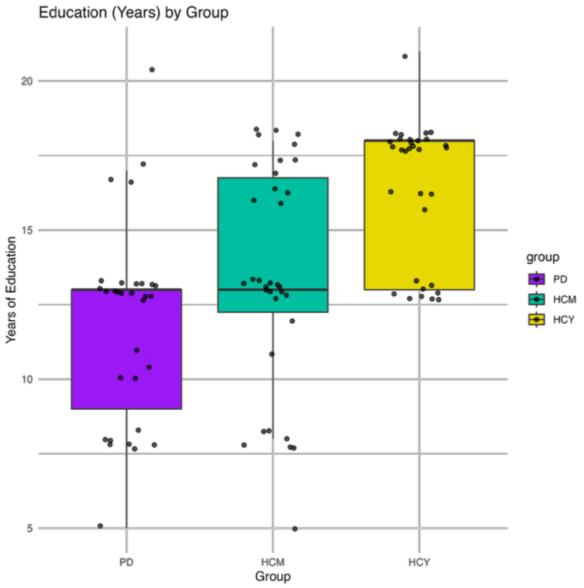


Figure 2. Distribution of Years of Education across Groups

Biological sex and handedness distributions were compared using Pearson's Chi-squared tests. As for PD vs. HCM, no significant differences were observed for biological sex ($p = .547$) or handedness ($p = .659$). Similarly, HCM and HCY did not differ significantly for biological sex ($p = .699$) or handedness ($p = .415$). Specifically, the PD group comprised 24 men and 7 women, the HCM group 23 men and 11 women, and the HCY group 24 men and 8 women. Regarding handedness, the PD group included 26 right-handed, 3 left-handed, and 2 ambidextrous participants; the HCM group 31 right-handed, 2 left-handed, and 1 ambidextrous participants, and the HCY group 28 right-handed and 4 left-handed participants (Figures 3 and 4).

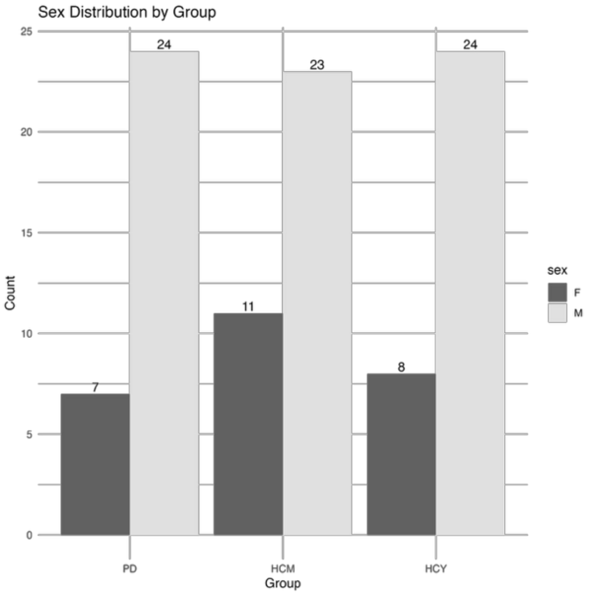


Figure 3. Distribution of Biological Sex across Groups

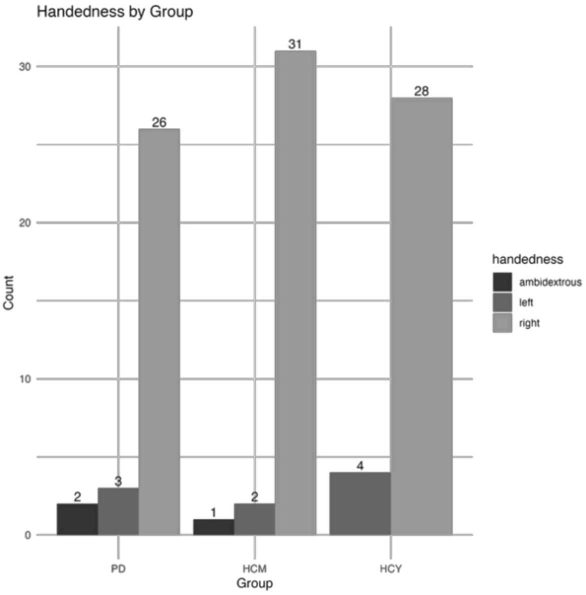


Figure 4. Distribution of Handedness across Groups

5.4 Neuropsychological Assessment

Neuropsychological testing was conducted during the first experimental session for all groups (PD, HCM and HCY). These standardised tests enabled characterisation of the participants' cognitive profiles. The assessment included the following neuropsychological measures, administered in this order: Frontal Assessment Battery (FAB), Montreal Cognitive Assessment (MoCA), and Hospital Anxiety and Depression Scale (HADS). During the second session, participants also completed an eye-tracking-based version of the Trail Making Test (TMT), Parts A and B.

5.4.1 Frontal Assessment Battery (FAB)

The Italian version of the Frontal Assessment Battery (FAB), recently validated and updated for the Italian population (Aiello et al., 2022b), was used as an assessment tool for executive functioning. Executive functions, which are typically impaired in diseases affecting cortical and subcortical frontal regions (Jurado & Rosselli, 2007; Godefroy et al., 2018), play a key role in supporting numerous cognitive processes. As a consequence, dysexecutive symptoms can substantially affect overall cognition and daily functioning. In PD, executive decline is often observed at the mild cognitive impairment (MCI) stage (Emre et al., 2007).

More specifically, the FAB comprises three subparts, each including two tasks scoring up to 3 points: FAB-1 corresponds to linguistically mediated executive functions and features a task of semantic similarity and a task phonemic verbal fluency (letter “S”); FAB-2 assesses planning and features a task of motor programming (Luria sequence, Luria, 1966/2012) and a task with conflicting instructions; FAB-3 targets inhibition and features a go-no-go task and a task assessing environmental autonomy (prehension behaviour). Administration requires approximately 5-10 minutes. The maximum total score is 18. Aiello et al. (2022b) provide age and education adjustment factors for FAB scores.

5.4.2 Montreal Cognitive Assessment (MoCA)

The Montreal Cognitive Assessment (MoCA) is a screening tool for mild cognitive impairment (MCI). It encompasses 13 tasks grouped into six cognitive domains: (1) executive functions, (2) visuospatial abilities, (3) language, (4) attention, (5) memory, and (6) orientation. Here are a detailed overview of task subdivision and score range for each subpart:

(1) Executive functions (score range 0-4): compact version of the Trail-Making-Test B (1 point), two-item semantic similarity abstraction task (2 points), phonemic verbal fluency task (1 point);
(2) Visuospatial abilities (score range 0-4): cube-copying task (1 point) and clock-drawing task (3 points);
(3) Language (score range 0-6): naming task with three animals (3 points), repetition of two syntactically complex sentences (2 points), phonemic verbal fluency task (1 point);
(4) Working memory, sustained attention, and concentration (score range 0-6): forward (1 point) and backward digit span (1 point), tapping-based target detection (1 point), serial subtraction task (3 points);
(5) Memory (score range 0-5): delayed recall of five nouns (5 points);
(6) Orientation (score range 0-6): questions on temporal and spatial orientation (6 points).

Administration requires approximately 10 minutes. Total raw scores range from a minimum of 0 to a maximum of 30 points and are corrected for age and education using normative data (e.g., Santangelo et al., 2015, for Italian populations). Following Santangelo et al. (2015), corrected MoCA scores can be calculated for each subpart and corrected individually, or summed together and then adjusted as follows:

$$\begin{aligned} &Adjusted\ MoCA\ score \\ &\qquad = raw\ MoCA\ score - 4.228 \times [log10(100 - age) - 1.58] \\ &\qquad - 3.201 \times [\sqrt{years\ of\ education - 3.25}] \end{aligned}$$

An overall score of 26 or higher is considered normal. Normal cognitive functioning, as assessed by the MoCA, was an inclusion criterion for participation.

5.4.3 Hospital Anxiety and Depression Scale (HADS)

The Hospital Anxiety and Depression Scale (HADS) is a tool to assess anxiety and depression in the form of a self-administered questionnaire. It consists of 14 statements divided equally between anxiety and depression items. Participants rate each statement by selecting the one option from four choices that best describes their emotional state. Each item is associated with a score from 0 to 3.

Scores ≤ 7 for each subscale (anxiety and depression) are considered normal; scores 8–10 indicate mild risk of developing psychopathological symptoms; scores ≥ 11 reflect a clinically relevant anxiety or depression state.

5.4.4 Trail Making Test (TMT)

The Trail Making Test (TMT) was originally developed in 1944 as part of the U.S. Army Individual Test Battery with the initial purpose to be used as a test of general intelligence of the soldiers. Two years later, the clinical psychologist Stewart G. Armitage proposed that the TMT was also a valuable tool to assess brain damage in soldiers who served in the Second World War (Armitage, 1946). Such neuropsychological relevance was also asserted by additional pioneering work in the ‘50s by one of the most prominent figures in neuropsychology, Ralph M. Reitan. Reitan replicated Armitage’s previous findings (1946) concluding that this advantageous test could constitute “a fairly valid indicator of certain effects of brain damage” (1955). The TMT is now considered a measure of executive functions and, in particular, set shifting capacities. “Set shifting”, also referred to as “set switching”, is the ability to quickly move from one mental schema to another to adapt to changing environmental stimuli.

The test is divided into two parts. In TMT-A, participants are asked to connect 25 numbered circles on a piece of paper using a pencil. In TMT-B, instead, the testing material contains both numbers and letters, and subjects have to alternate one number and one letter by connecting 1 to A, A to 2, 2 to B, etc. Collected measures are time to complete each subpart of the test and accuracy of the responses (two versions, see Reitan, 1955). The original, paper-based version of the test involves a certain amount of motor control, since it requires to hold a pencil and trace accurate lines to connect the dots one with the other. This aspect makes the test less suitable for people experiencing motor impairments, such as people with PD. The identification of abnormally longer times or lower accuracy rates in this and other similar populations having inherent motor impairment would represent an unreliable measure of set shifting capacities, as the cognitive and the motor components would be hard to tear apart from each other. According to Bowie & Harvey (2006), Part A of the TMT reflects motor performance, while Part B has more cognitive demands, including set shifting, response inhibition, working memory. By subtracting the time taken to complete TMT-A to the time taken to complete TMT-B, it would be possible to obtain the "TMT delta", which isolates the cognitive component and can be considered a purely cognitive measure.

Another possibility that allows limiting the motor demands of the task involves converting it to electronic format. The only attempt at devising an electronic version of the test is represented by Schmitz-Peiffer and colleagues (2022). The authors of this study, who refer to their version of the test as eTMT, evaluated their design in two clinical populations, namely PD and amyotrophic lateral sclerosis (ALS). In our study, we also employed an eTMT based on the eye-tracking technology, that required participants to browse the screen with their eyes to search for the next number or letter. All items were located in the same areas as in the original paper version of the test. Once the participant fixated the target area of interest (AOI) for 200 ms, long enough to consciously perceive and therefore select the target answer, a line appeared to connect the target to the previous response (Figure 5). The collected measures were total completion time for TMT-A and total completion time for TMT-B (both expressed in seconds).

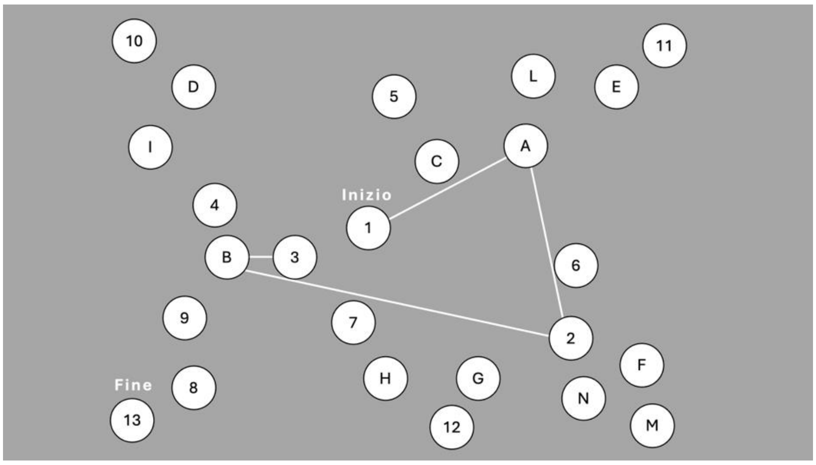


Figure 5. Example from our eye-tracking-based version of TMT-B

5.4.5 Neuropsychological Assessment Results

Between-group comparisons on neuropsychological measures are summarised in Tables 5 and 6. Table 5 reports the contrasts between the PD and HCM groups, while Table 6 presents the corresponding comparison between HCM and HCY participants.

Table 5. Neuropsychological assessment PD vs HCM

Neuropsychological variables	PD (*N* = 31)	HCM (*N* = 34)	*p*-value	Test
fab_total	15.81 (2.33)	17.18 (0.80)	0.012*	Wilcoxon
fab_1	5.13 (0.99)	5.53 (0.56)	0.110	Wilcoxon
fab_2	5.23 (1.06)	5.94 (0.24)	< 0.001***	Wilcoxon
fab_3	5.45 (0.89)	5.71 (0.63)	0.236	Wilcoxon
total_moca_raw	26.00 (2.54)	26.12 (2.32)	0.853	Wilcoxon
total_moca_corr	25.67 (2.11)	25.10 (2.4)	0.311	t-test
total_executive_functions_corr	2.24 (0.75)	2.23 (0.68)	0.808	Wilcoxon
total_visuospatial_corr	3.03 (0.91)	3.00 (0.83)	0.896	t-test
total_language_corr	5.17 (0.82)	5.10 (0.66)	0.723	t-test
total_attention_corr	5.79 (0.42)	5.48 (0.60)	0.020*	t-test
total_memory_corr	3.48 (1.29)	3.32 (1.27)	0.735	Wilcoxon
total_orientation_corr	5.99 (0.18)	6.01 (0.05)	0.261	Wilcoxon
hads_anxiety	5.45 (3.26)	4.56 (2.64)	0.252	Wilcoxon
hads_depression	5.13 (2.78)	3.53 (2.75)	0.016*	Wilcoxon
eTMT-A	84.41 (62.87)	59.23 (37.59)	0.025*	Wilcoxon
eTMT-B	170.22 (129.97)	105.89 (73.61)	0.016*	Wilcoxon

(* $p < .05$, ** $p < .01$, *** $p < .001$)

Table 6. Neuropsychological assessment HCM vs HCY

Neuropsychological variables	HCM (*N* = 34)	HCY (*N* = 32)	*p*-value	Test
fab_total	17.18 (0.80)	17.53 (0.57)	0.066	Wilcoxon
fab_1	5.53 (0.56)	5.66 (0.48)	0.382	Wilcoxon
fab_2	5.94 (0.24)	6.00 (0.00)	0.174	Wilcoxon
fab_3	5.71 (0.63)	5.88 (0.34)	0.238	Wilcoxon
total_moca_raw	26.09 (2.30)	28.34 (1.66)	< 0.001***	Wilcoxon
total_moca_corr	25.10 (2.40)	24.61 (2.10)	0.320	t-test
total_executive_functions_corr	2.23 (0.68)	1.80 (0.66)	0.006**	Wilcoxon
total_visuospatial_corr	3.00 (0.83)	2.87 (0.64)	0.308	Wilcoxon
total_language_corr	5.10 (0.66)	5.00 (0.44)	0.400	Wilcoxon
total_attention_corr	5.48 (0.6)	5.30 (0.58)	0.320	Wilcoxon
total_memory_corr	3.32 (1.27)	4.44 (0.91)	< 0.001***	Wilcoxon
total_orientation_corr	6.01 (0.05)	5.83 (0.02)	< 0.001***	Wilcoxon
hads_anxiety	4.56 (2.64)	5.88 (3.42)	0.095	Wilcoxon
hads_depression	3.53 (2.75)	3.97 (3.27)	0.708	Wilcoxon
eTMT-A	59.23 (37.59)	30.92 (13.25)	< 0.001***	Wilcoxon
eTMT-B	105.89 (73.61)	54.98 (20.27)	< 0.001***	Wilcoxon

(* $p < .05$, ** $p < .01$, *** $p < .001$)

Note. PD = people with Parkinson's disease; HCM = matched healthy controls; HCY = younger healthy controls; fab_total: overall score of the Frontal Assessment Battery (FAB); fab_1: linguistic executive functions; fab_2: planning; fab_3: inhibition; total_moca_raw: raw score of the Montreal Cognitive Assessment (MoCA); total_moca_corr: MoCA score adjusted following Santangelo et al. (2015); hads_anxiety: anxiety subscale score of the Hospital Anxiety and Depression Scale (HADS); hads_depression: depression subscale score of HADS; eTMT-A: total completion time for the eye-tracking-based Trail Making Test, Part A (ms); eTMT-B: total completion time for Part B (ms).

No significant differences emerged between PD and HCM in global cognitive functioning as assessed by either the MoCA raw score (PD: $M = 26.00$, $SD = 2.54$; HCM: $M = 26.12$, $SD = 2.32$; $p = 0.85$, ns) or MoCA corrected scores (PD: $M = 25.67$, $SD = 2.11$; HCM: $M = 25.10$, $SD = 2.40$; $p = 0.31$, ns). These results confirm that both groups were cognitively intact and did not present any sign of mild cognitive impairment or dementia. At the subdomain level, no significant differences were found between PD and HCM participants across visuospatial abilities, language, memory, orientation, or executive functions. The only exception was the attention subscore, where PD performed better than HCM ($p = .020$). Given that MoCA attention items assess basic attentional processes (digit span, vigilance, subtraction capacities), these results likely reflect preserved low-level attention in early-stage PD. Overall, PD and HCM displayed highly comparable cognitive profiles, suggesting that the PD sample represents a well-preserved and non-demented cohort. As illustrated by the radar plot (Figure 6), PD participants and their demographically similar healthy controls show nearly identical cognitive profiles across MoCA domains.

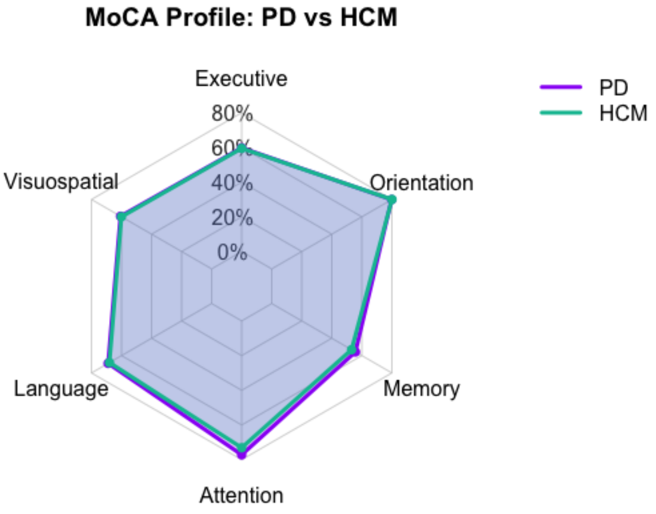


Figure 6. Radar Plot Illustrating MoCA Domain Scores across PD and HCM Participants

When comparing HCM to HCY, HCY performed significantly better on the MoCA raw score (HCY: *M* = 28.34, *SD* = 1.66; HCM: *M* = 26.12, *SD* = 2.32; *p* < 0.001 ***), but no significant difference was observed for the corrected score (HCY: *M* = 24.61, *SD* = 2.10; HCM: *M* = 25.10, *SD* = 2.40; *p* = 0.38, ns). This pattern is fully expected because the MoCA correction procedure explicitly adjusts for age and education, which are the demographic characteristics that differ significantly between HCM and HCY. As a result, the adjusted scores remove the advantage linked to younger age and higher education in the HCY group. This highlights the relevance of using corrected MoCA values when interpreting cognitive performance, as they better isolate true cognitive status from demographic influences.

At the subdomain level (Figure 7), HCY performed significantly better than HCM on memory (*p* < 0.001), whereas HCM scored significantly higher on executive functions (*p* = .006) and orientation (*p* < 0.001). These latter differences should not be interpreted as cognitive impairment in HCY but rather as artefacts of demographic correction, which penalises younger individuals, and ceiling effects inherent to simple MoCA items (e.g., abstraction, trail making, orientation to place/time). No significant differences were found in visuospatial abilities, language, or attention.

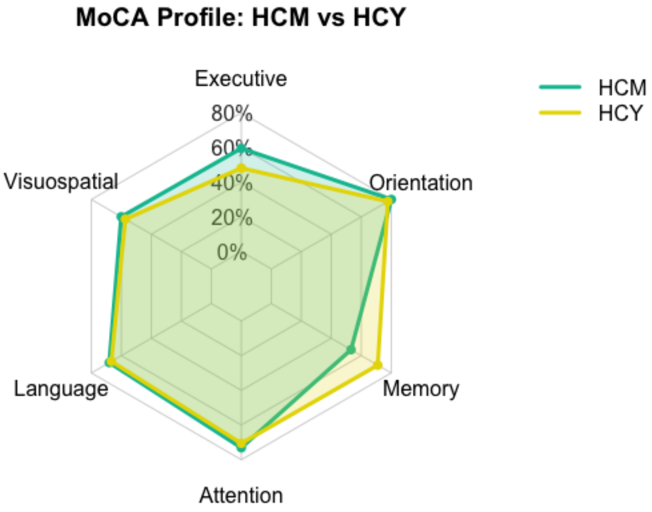


Figure 7. Radar Plot Illustrating MoCA Domain Scores across HCM and HCY Participants

Performance on the Frontal Assessment Battery (FAB) total score significantly differed between PD and HCM groups, with the HCM group outperforming the PD group (PD: *M* = 15.81; *SD* = 2.33; HCM: *M* = 17.18, *SD* = 0.80; *p* = .012). As can be observed from the corresponding plot (Figure 8) and descriptive values (Table 5), HCM showed better global executive functioning than PD. At the subdomain level, no significant group differences emerged for the Linguistically mediated EF subscale (FAB-1; PD: *M* = 5.13, *SD* = 0.99; HCM: *M* = 5.53, *SD* = 0.56; *p* = 0.110) or for the Inhibition subscale (FAB-3; PD: *M* = 5.45, *SD* = 0.89; HCM: *M* = 5.71, *SD* = 0.63; *p* = 0.236). The only significant effect was observed for the FAB Planning subscale (FAB-2), which includes tasks such as Luria motor sequences and conflicting instructions, where HCM scored higher than PD (PD: *M* = 5.23, *SD* = 1.06; HCM: *M* = 5.94, *SD* = 0.24; $p < 0.001$).

When comparing HCM and HCY, no statistically significant differences emerged on the FAB total score (HCM: *M* = 17.18, *SD* = 0.80; HCY: *M* = 17.53, *SD* = 0.57; *p* = 0.066), although HCY showed a slight trend toward higher performance consistent with their younger age. Likewise, the subscale scores did not differ significantly between groups on FAB-1 (*p* = 0.382), FAB-2 (*p* = 0.174), or FAB-3 (*p* = 0.238). The pattern of results indicates that executive functioning was largely preserved across all groups, with PD showing vulnerability in the Planning subscale.

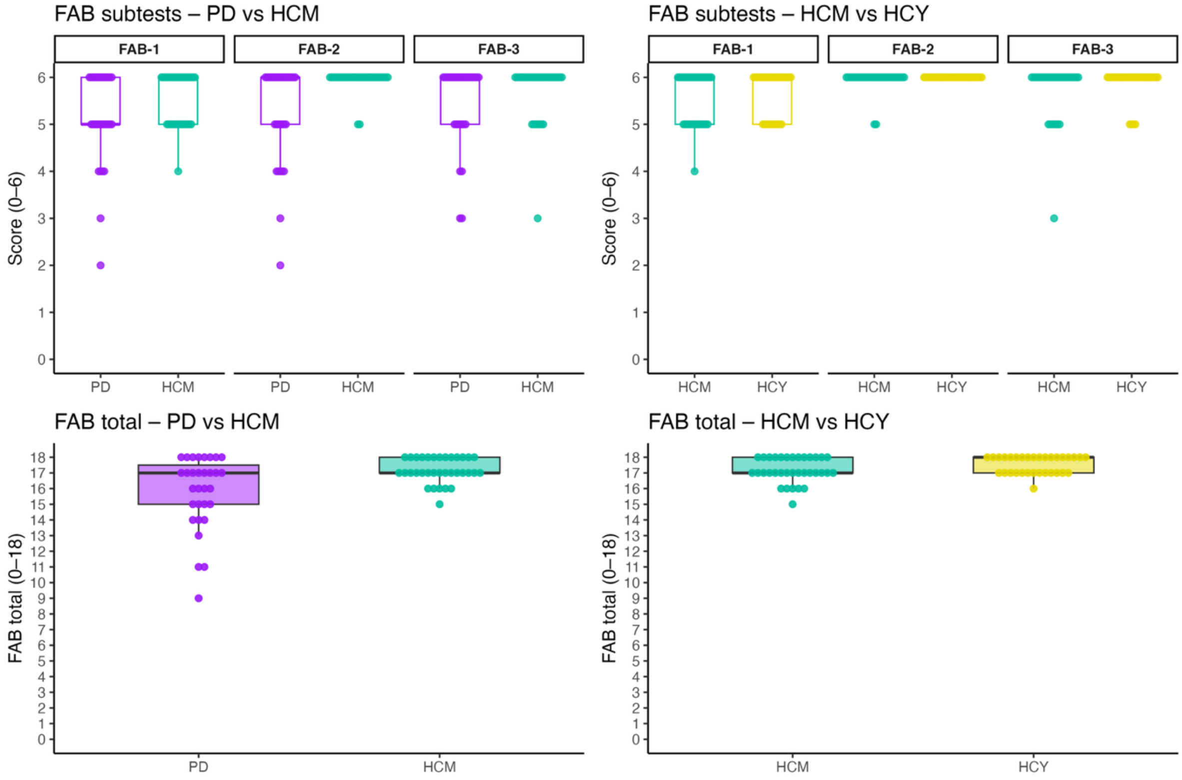


Figure 8. Executive Functions as Assessed through the Frontal Assessment Battery (FAB)

Note. FAB-1 = Linguistically Mediated Executive Functions subscale; FAB-2 = Planning subscale; FAB-3 = Inhibition subscale.

Regarding affective symptoms, no significant difference emerged between PD and HCM participants on the HADS Anxiety subscale (*p* = .252), indicating comparable levels of anxiety across these two groups. In contrast, depression scores were significantly higher in the PD group (*p* = 0.016), compared to the control group. Although mean depression scores in both groups remained well below the clinical cutoff for probable depression, this difference is consistent with the well-documented tendency for people with early-stage PD to experience mild affective disturbances. Overall, these results suggest that PD participants exhibit slightly elevated depressive symptoms relative to matched controls, while anxiety levels remain largely comparable (Figure 9, see also Table 5).

When comparing HCM and HCY participants, no significant differences were observed in depressive symptoms ($p = .708$) or anxiety symptoms ($p = .095$). Although HCY displayed a non-significant trend toward higher anxiety scores, both groups remained within the non-clinical range.

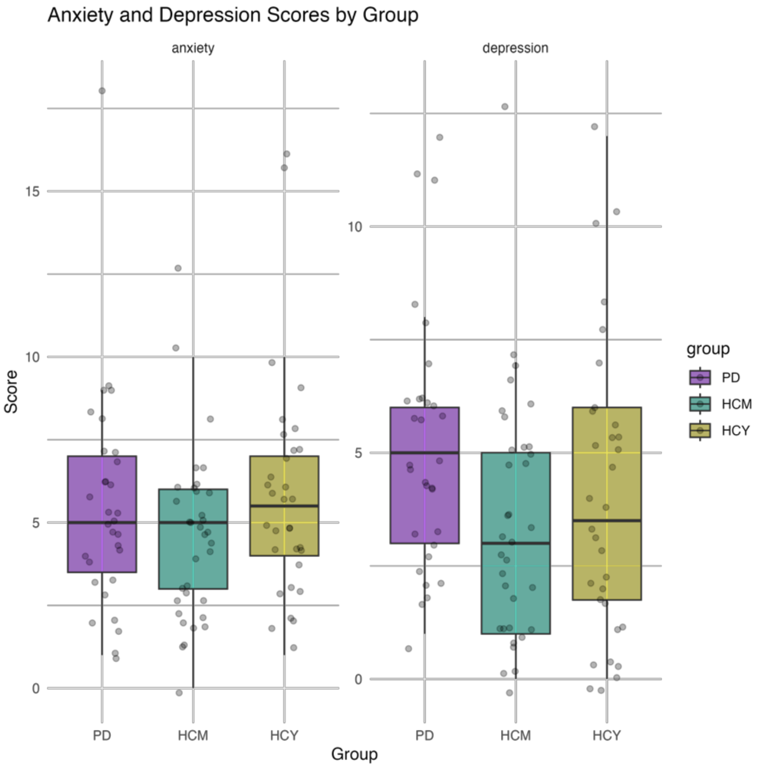


Figure 9. Anxiety and Depression as Assessed through the Hospital Anxiety and Depression Scale (HADS)

Performance on the Trail Making Test revealed clear group differences in processing speed and set-shifting capacities. In particular, participants with PD required significantly more time than their demographically matched healthy controls to complete both TMT-A and TMT-B. Completion times were higher in the PD group for TMT-A (PD: $M = 84.41$ s, $SD = 62.87$; HCM: $M = 59.23$ s, $SD = 37.59$; $p = .025$) and TMT-B (PD: $M = 170.22$ s, $SD = 129.97$; HCM: $M = 105.89$ s, $SD = 73.61$; $p = .016$). This pattern reflects reduced processing speed and diminished set-shifting efficiency in individuals with PD compared to matched controls, consistent with executive slowing frequently observed in PD.

When comparing older and younger healthy participants, HCY performed significantly faster than HCM on both subparts (TMT-A: HCY $M = 30.92$ s, $SD = 13.25$; TMT-B $M = 54.98$ s, $SD = 20.27$; both $p < .001$), confirming a robust age-related decline in executive control and cognitive flexibility, with younger adults showing the expected advantage on both simple (TMT-A) and complex (TMT-B) sequencing tasks (Figure 10).

Across all neuropsychological measures, PD participants showed a broadly preserved cognitive and affective profile, with only subtle weaknesses emerging in executive domains. MoCA performance was comparable between PD and matched controls; on the FAB, PD exhibited reduced planning abilities, while global executive functioning remained within the normal range. Affective symptoms were generally mild, though PD reported higher depressive scores than HCM. Finally, TMT performance revealed clear slowing in PD and a pronounced age effect among healthy participants.

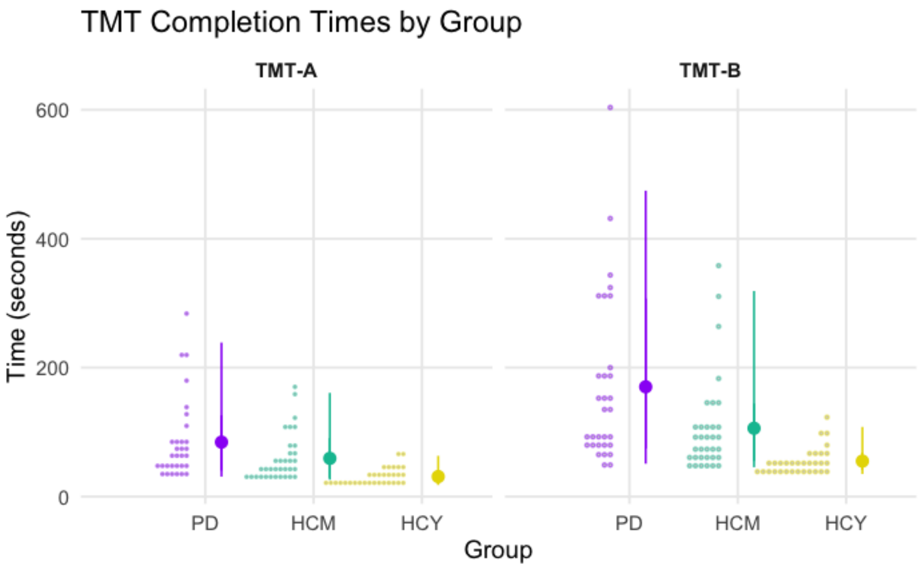


Figure 10. Set Shifting as Assessed through the Eye-Tracking-Based Trail Making Test (TMT), Parts A and B

5.5 Clinical Assessment

Participants with PD additionally underwent a complete neurological examination administered by their treating neurologist. The evaluation included all subscales of the Unified Parkinson's Disease Rating Scale (UPDRS): UPDRS-I, UPDRS-II, UPDRS-III and UPDRS-IV. Other clinical and therapeutic parameters were also collected, such as age of onset, disease duration, most affected side, PD phenotype, pharmacological therapy, L-dopa equivalent daily dose (LEDD), dopamine agonist equivalent daily dose, time since last medication intake, and Hoehn and Yahr (H&Y) staging of disease severity (Hoehn & Yahr, 1967). Table 7 summarises these measures (group means followed by standard deviations in parentheses). Categorical variables (most affected side and phenotype) are reported as absolute frequencies.

5.5.1 Unified Parkinson's Disease Rating Scale (UPDRS)

The Unified Parkinson's Disease Rating Scale (UPDRS) is the gold-standard clinical tool for quantifying symptom severity and functional impairment in PD (Goetz et al., 2008). It provides a comprehensive overview of motor and non-motor symptoms, encompassing four main parts: UPDRS-I (Mentation, Behaviour, and Mood) assesses cognitive status, emotional well-being, and psychiatric manifestations; UPDRS-II (Activities of Daily Living) evaluates the individual's self-reported capacity to perform daily tasks such as eating, dressing, and personal hygiene; UPDRS-III (Motor Examination) involves clinician-related evaluation of tremor, rigidity, bradykinesia, posture, and gait; UPDRS-IV (Complications of Therapy) documents dyskinesias, fluctuations, and other complications arising from dopaminergic treatment.

In this study, UPDRS assessments were performed while participants were in the "OFF" medication state, ensuring that symptom ratings reflected their baseline motor condition rather than pharmacological compensation. All clinical indices used to characterise the PD sample are reported in Table 7.

Table 7. Clinical Characteristics of the PD Group

Age at onset (years)	61.2 (7.03)
Disease duration (years)	3.57 (2.14)
Most affected side	16 right; 15 left
Phenotype	23 tremor-dominant; 8 akinetic-rigid
LEDD	358 (181)
LEDD-DA	57.5 (67.7)
UPDRS-I (Mentation, Behaviour, and Mood)	9.70 (5.14)
UPDRS-II (Activities of Daily Living)	6.47 (4.61)
UPDRS-III (Motor Examination)	21.60 (8.63)
UPDRS-IV (Complications of Therapy)	0.00
Hoehn & Yahr (H&Y) stage	1.77 (0.41)

Note. Reported values reflect means with standard deviations in parentheses, *M* (*SD*).

LEDD = L-dopa equivalent daily dose; LEDD-DA = dopamine agonist equivalent daily dose.

UPDRS = Unified Parkinson's Disease Rating Scale. The range of each scale is: UPDRS-I = 0-16, UPDRS-II = 0-52, UPDRS-III = 0-108, UPDRS-IV = 0-23, with higher scores indicating worse symptoms.

Hoehn & Yahr (H&Y) stages: 1 = unilateral involvement only, 1.5 = unilateral plus axial involvement, 2 = bilateral involvement without impairment of balance, 2.5 = mild bilateral disease with recovery on pull test, 3 = mild to moderate bilateral disease with some postural instability, 4 = severe disability but still able to walk or stand unassisted, 5 = wheelchair-bound or bedridden unless aided.

5.6 Summary and Conclusions

Due to our matching procedure, the two groups included in this research, PD and HCM, were closely comparable across all relevant background variables, with no significant differences in age, education, biological sex, or handedness. Both groups demonstrated preserved global cognition, as evidenced by MoCA scores within the normal range and with no indication of mild cognitive impairment or dementia. Their cognitive profiles across domains overlapped substantially. Neuropsychological testing further showed that, although PD participants exhibited the characteristic pattern associated with early-stage PD, namely subtle weaknesses in planning, slowed processing speed and reduced set shifting (as reflected in FAB-2 and TMT performance), these differences were mild and occurred against a backdrop of generally intact executive, attentional, and visuospatial abilities. Affective symptoms were low in both groups, with comparable levels of anxiety and slightly higher but still subclinical depression scores in PD. Clinical assessment confirmed that the PD sample corresponded to a mildly affected cohort, with Hoehn & Yahr staging and UPDRS scores consistent with early idiopathic PD. Overall, the neuropsychological and clinical data indicate that PD and HCM participants were cognitively preserved with no signs of MCI, and suitably matched for the experimental investigations reported in the subsequent chapters.

Chapter 6 – Lexical Access and Semantic Competence in Parkinson’s Disease (Study 1)

To investigate the interplay between conceptual and linguistic factors in lexical retrieval in PD (see also Chapter 2, Section 2.4.2, *Models of Lexical Access, Selection, and Control*), we employed a picture-naming paradigm comparing the performance of individuals with PD to that of matched neurotypical controls.

For verbs, a central linguistic dimension is argument structure, since its complexity may impose additional processing demands on people with PD. Another relevant linguistic dimension for this part of speech is agentivity, operationalised within Reinhart’s (2002) Theta System as the presence of a subject bearing the feature cluster [+c+m], which jointly encodes causal responsibility ([+c]) and intentional mental involvement ([+m]) in the event expressed by the verb. Within the Theta System framework (Reinhart, 2002; Marelj, 2004), the conceptual system and the linguistic system interact through a dedicated interface. For syntax to access conceptual information, concepts must be made legible by formally encoding them, a procedure provided by the Theta System itself. In particular, concepts are represented as feature clusters composed of two binary features, [± c] (cause change) and [± m] (mental state), each of which may be either fully specified or underspecified. This distinction allows the system to capture contrasts such as the difference between fully specified roles, such as the external-role cluster [+c+m] associated with verbs like *eat*, which denote events involving both causation and intentional participation, and underspecified roles, such as the [+c] external cluster found with verbs like *break*, which encode causation without mental involvement.

These examples illustrate that verb entries consist of feature clusters that encode the basic causal and mental relations relevant for both syntactic realisation and semantic interpretation. The argument structure of a verb follows from the configuration of these clusters, which determines how many arguments are conceptually required and how they are mapped to syntactic positions. Crucially, the Theta System maintains that different surface realisations of a verb, such as the causative-inchoative alternation (*Sara broke the window* vs. *The window broke*) or the absence of an unaccusative counterpart for verbs like *eat*, are not stored as independent lexical items. Instead, they are derived from a single underlying lexical entry via lexical operations. For example, expletivisation reduces the verb’s arity by eliminating the external argument, and causativisation expands the verb’s grid by adding an external [+c] role, and these operations apply only when certain feature-based conditions are met.

Within this system, agentivity corresponds to the presence of a [+c+m] cluster in subject position. This distinguishes agentive verbs, those requiring an agentive subject entailing both causation and intention, from non-agentive ones, whose subjects lack one or both components. Other roles are likewise defined compositionally, such as *experiencers* ([-c+m]), *instruments* ([+c-m]), or *themes/patients* ([-c-m]). Table 8 summarises the nine feature clusters proposed by Reinhart (2002) and illustrates their typical role interpretations. The first four are fully specified clusters, while the remaining five correspond to underspecified clusters. These clusters capture fine-grained distinctions necessary for analysing the presence or absence of agentivity in our experimental materials, thereby providing the theoretical basis for the manipulation of agentivity implemented in the present study.

Table 8. Nine Feature Clusters (Adapted from Reinhart, 2002)

Feature Cluster	Typical θ-Role	Example Verbs / Notes
[+c+m]	agent	e.g., *eat*, *shave*
[+c-m]	instrument	context-dependent; e.g., *open*, *break*
[-c+m]	experiencer	psychological verbs
[-c-m]	theme/patient	unaccusatives: *fall*, *freeze*, *grow*
[+c]	cause	underspecified: allows agent / instrument / causer realisations
[+m]	sentient	subjects of *love*, *believe*
[-m]	subject matter/locative source	oblique arguments
[-c]	goal/benefactor	typically realised as PP/dative
[ ]	arbitrary	operative in middle-formations (Marelj, 2004)

On this basis, we predicted that verbs with more complex argumental specifications would require higher retrieval demands. It is important to note that, within the Theta System, argument-structure complexity is not defined simply in terms of the number of syntactic arguments a verb takes, but in terms of the operations required to licence their syntactic form, namely operations such as expletivisation, saturation, or causativisation, which derive the various surface realisations from a single underlying entry (Reinhart 2002; Reinhart & Siloni, 2005). Verbs whose feature clusters permit or require such operations involve a more articulated derivational process in the lexicon. In contrast, verbs whose θ-grid is realised without the need for such operations display a less complex lexical architecture. This operational view of complexity, rather than a merely structural one based on the number of arguments, provides the basis for our predictions regarding increased retrieval demands in PD.

As for nouns, a comparable linguistic dimension that distinguishes between different nominal classes is their *qualia* structure, the central representational component of Pustejovsky's Generative Lexicon framework (Pustejovsky, 1991; 1995). Crucially, the Generative Lexicon (GL) is not a theory of conceptual structure *per se*, but a linguistic theory of lexical representation that formally encodes those aspects of conceptual knowledge that are linguistically relevant. As Pustejovsky puts it, "without an appreciation of the syntactic structure of a language, the study of lexical semantics is bound to fail. There is no way in which meaning can be completely divorced from the structure that carries it" (1991: 410). In other words, GL models how conceptual distinctions become linguistically legible. In developing this framework, Pustejovsky positions qualia structure at the interface between conceptual organisation and linguistic expression. Thus, qualia roles represent linguistically encoded projections of conceptual knowledge, not conceptual categories themselves.

This position distinguishes GL from two major traditions in lexical semantics, namely primitives-based approaches (Wilks 1975; Katz 1972; Lakoff 1971; Schank 1975), which assume that meanings can be decomposed into a fixed stock of atomic conceptual primitives, and relation-based or network approaches (Quillian 1968; Collins and Quillian 1969; Fodor 1975; Carnap 1956; Brachman 1979), which treat lexical knowledge as an associative web without internal semantic structure. Against both, Pustejovsky argues that lexical meaning exhibits internal organisation, but such decomposition must be generative and grounded in the operations of the linguistic system rather than in universal primitives or unconstrained semantic networks.

His principled method for lexical decomposition presupposes a rich, recursive theory of semantic composition, the notion of semantic well-formedness, and an appeal to several levels of interpretation in the semantics. In the GL, the semantics of a lexical item α is represented as a structured 4-tuple:

$$\alpha = < A, E, Q, I >$$

A encodes its argument structure, *E* its event structure, *Q* corresponds to its *qualia* structure, which binds the above levels, and *I* is its inheritance structure within the global organisation of the lexicon. These four levels are then connected by a set of generative devices, such as semantic transformations (type coercion, selective binding, co-composition).

Among these components, *qualia* structure is the one most directly relevant for distinguishing nominal classes. It decomposes a nominal lexical entry into its minimal semantic configuration, capturing components such as its constitutive, telic, agentive, and formal roles. The constitutive role captures part-whole relations and material composition (although this dimension was not examined in the current study), the telic role expresses the built-in purpose or intended function of the entry, the agentive role specifies how the entry comes into being, either through natural processes or human creation, and the formal role distinguishes the entity within a broader taxonomy, and encompasses features such as shape, orientation, magnitude, and dimensionality (Table 9).

Together, these dimensions define the internal semantic structure of the noun. In this respect, *qualia* structure stands in parallel to Reinhart's feature-cluster system for verbs. Just as Reinhart formalises conceptual distinctions concerning causation and mental involvement so that the Theta System can make them accessible to syntax, Pustejovsky formalises conceptual distinctions concerning composition, origin, function, and shape so that the lexical and compositional system can exploit them. In both models, linguistic structures serve to mediate conceptual knowledge.

Table 9. The Four Qualia Roles Defined in Pustejovsky's Generative Lexicon

Qualia Role	Semantic Contribution	Description
Constitutive	Internal makeup	Encodes part-whole relations, material composition, and inherent physical properties.
Telic	Function / purpose	Specifies the default or intended function of the entity.
Agentive	Origin / creation	Describes how the entity came into being, including natural processes or human manufacturing.
Formal	Taxonomic identity	Defines the basic category of the entity and its distinguishing properties (e.g., shape, orientation, dimensionality).

In the present context, nouns with telic or agentive qualia are expected to impose higher retrieval demands in individuals with PD, who may show reduced capabilities in accessing or integrating the associated semantic information, which has to do with goal-directed action and agentivity.

To date, the differential contributions of action-relatedness (a conceptual-level dimension) and argumental or qualia structure (linguistic-level variables) to lexical access in PD have not been explored.

Based on prior literature, we predicted that individuals with PD would exhibit reduced naming accuracy and longer latencies relative to controls. Moreover, we further hypothesised that lexical items conjuring up action-related concepts should trigger increased naming difficulty in the PD group. In addition, we expected linguistic complexity, reflected in verbs with more complex argument structures caused by required lexical operations on the verbal θ-grid, the presence of agentivity, and in nouns with richer *qualia* structures, to negatively impact naming performance in PD. Finally, we anticipated a potential interaction between conceptual and linguistic dimensions, such that retrieval difficulty would be greatest when both conceptual and linguistic demands were high.

6.1 Picture-Naming Task

6.1.1 Stimuli

To address our research questions, we selected 49 nouns and 35 verbs, and we created coloured pictures representing them using the AI text-to-image generation software *DALL-E*. To rate the association between each picture and its target caption, we employed the visual-language model (VLM) *CLIP*, which allowed us to retrieve similarity scores for each picture-target word pair. These scores provided a measure of “picture goodness”, the extent to which each image accurately represented the intended word and therefore allowed us to control for low-level perceptual factors that might affect naming performance.

To investigate whether language-specific characteristics modulated naming performance, verb stimuli were classified into five categories based on their argumental structure and aspectual features. The following verbal categories were defined: two classes of transitive verbs (accomplishments and achievements) (Vendler, 1957), and three classes of intransitive verbs (unaccusatives, unergatives, and unergatives with internal agentivity (Pinker, 2007)). Verb typology distinguishes verbs based on their syntactic and semantic properties, such as the number of the internal and external arguments that they take, the nature of such arguments, and the semantics expressed by the verb (Levin, 1993).

Moreover, verbs were further classified as "agentive" or "non-agentive" following Reinhart (2002). More particularly, agentive verbs were identified based on the presence of an external argument bearing the theta-feature cluster [+c+m], which marks the subject as both the intentional initiator and the cause of the event (e.g., *to build*). In contrast, non-agentive verbs included those whose external arguments bear feature clusters such as [+m] (e.g., *to laugh*, sentient) or [-c-m] (e.g., *to faint*, theme or patient), reflecting either mental involvement without causation or complete lack of intentional and causal feature, respectively. Examples of verb stimuli are provided in Table 10. The full list of stimuli used in this study is provided in Appendix 1.

Table 10. Examples of Verb Stimuli and Categories

Item	Linguistic Category	Agentivity	Action-relatedness score
scrive ("he/she writes")	transitive (accomplishment)	agentive	4.26
arresta ("he/she arrests")	transitive (achievement)	agentive	5.32
scivola ("he/she slips")	unaccusative	non-agentive	7.15
pattina ("he/she skates")	unergative	agentive	7.89
sbadiglia ("he/she yawns")	unergative (internal agentivity)	non-agentive	3.68

Note. The *action-relatedness scores* reflect the average ratings given by an independent group of 20 raters, who were presented with each verb-picture combination in a random order and asked, for each of them, to "assess the level of movement required by the action expressed by each verb on a scale from 1 to 9, where 1 indicates no movement and 9 indicates a very high degree of movement".

Noun stimuli were classified into seven categories based on their *qualia* structure, capturing the essential attributes of a lexical item (Pustejovsky, 1991; 1995). *Qualia* roles form a set of relations essential for capturing the meaning of lexical items. For example, the hypothesis is that the meaning of the word *screwdriver* cannot be properly understood without reference to its function, i.e., its telic quale.

Based on this framework, seven noun categories were created: shapes (formal quale), natural kinds (agentive quale: natural type), tools (telic quale), ready-to-eat food (telic quale), food requiring a hand action (telic quale), food requiring a tool action (telic quale), and artefacts (agentive quale: result of an action). Examples of noun stimuli are provided in Table 11, and the full list of stimuli used in this study is provided in Appendix 1.

Table 11. Examples of Noun Stimuli and Categories

Item	Linguistic Category	Action-relatedness score
cerchio ("circle")	shapes	1.50
nuvola ("cloud")	naturals	1.50
cucchiaio ("spoon")	tools	8.19
minestra ("soup")	ready-to-eat	6.25
mandarino ("tangerine")	hand action	8.25
anguria ("watermelon")	tool action	7.81
impronta ("footprint")	artefacts	3.38

Note. The *action-relatedness scores* reflect the average ratings given by an independent group of 20 raters, who were presented with each noun-picture combination in a random order and asked, for each of them, to "assess the level of manipulability of the object expressed by each noun on a scale from 1 to 9, where 1 indicates no manipulability and 9 indicates very high manipulability. By 'manipulability', we mean the ease with which an object can be grasped, controlled, and handled by an agent".

The frequency of word forms for all stimuli was retrieved from the Italian Web 2020 (*itTenTen20*) corpus through Sketch Engine. Because frequency effect is a low-level one, and given that verbal stimuli were elicited using the third person singular of the verb by prompting the participant asking "What does this person do?" (*Cosa fa questa persona?*), frequency values for the individual third person singular word forms were selected rather than their lemmas (e.g., *go*, *went*, *gone*, *goes*, *going* are word forms of the lemma *go*). Additionally, the frequency values considered for the analysis were the $\log_{10}$-transformed absolute frequency (Van Heuven et al., 2014; Brysbaert et al., 2018). When plotted against log-transformed ranks, the distribution followed Zipf's law with some curvature, likely due to the limited dataset size.

To rate the degree of action-relatedness associated with each image, we carried out two rating studies involving 20 Italian native speakers with no language or learning disorder (age: $M = 30.21$; $SD = 6.54$). Nominal stimuli were rated based on their *manipulability*, defined as the ease with which an object can be grasped, controlled, and handled by an agent. Verbal stimuli were instead rated based on their *motion*, namely the amount of movement required to perform the action described by each verb. Participants completed an online questionnaire using 9-point Likert scales, rating verb and noun stimuli separately. Each item of the questionnaire consisted in the target word and its corresponding picture. Nouns were rated from "no manipulability" (1) to "high manipulability" (9), and verbs from "no motion" (1) to "high motion" (9). Such ratings were averaged across participants to derive an "action-relatedness score" for each item. The complete list of stimuli appears in Appendix 1.

6.1.2 Procedure

Each participant was tested individually in a quiet environment and was instructed to name each picture by using a single word. Visual stimuli, divided into nouns and verbs, were presented one at a time in random order. For noun stimuli, participants were prompted to name the object or entity depicted following the instruction “What is this?” (*Che cos’è questo?*). For verb stimuli, responses were elicited in the third person singular of the verb by asking the participant “What does this person do?” (*Cosa fa questa persona?*). Pictures were displayed on the screen using *E-Prime* software (version 3.0; Psychology Software Tools; see Figure 11). In each trial, after a 500-ms blank screen, a fixation cross appeared in the centre of the screen for 500 ms, followed by the picture stimulus. Participants had a maximum of 7 seconds to provide a verbal response and press the spacebar to proceed to the next trial. If no response was given within the allotted time, the trial was scored as an omission. Both accuracy and reaction times (speech onset) of verbal responses were collected. Five training items were administered for both nouns and verbs before proceeding with the experimental naming trials.

For noun accuracy coding, single-word noun responses matching the standard item name or a valid synonym (e.g., *anguria* and *cocomero* for “watermelon”) were scored as correct (1 point). Six error types were scored as incorrect (0 points): Type 1 – Omission (e.g., “I don’t know”); Type 2 – Syntactic category errors (non-noun responses such as verbs or adjectives); Type 3 – Semantically related responses (e.g., *rettangolo* “rectangle” for *triangolo* “triangle”); Type 4 – Superordinate responses (e.g., *frutto* “fruit” for *albicocca* “apricot”); Type 5 – Proper name substitutions (e.g., *Etna* for *vulcano* “volcano”); Type 6 – Image-decoding errors (e.g., *uovo* “egg” for *ovale* “oval”). Additionally, after discarding all error-bearing responses, we annotated two correct response types: Remark 1 – Morpho-syntactic variations (e.g., *carote* “carrots” for *carota* “carrot”); Remark 2 – Descriptive additions (e.g., *una torta al cioccolato* “a chocolate cake” for *torta* “cake”). These were considered accurate as far as lexical retrieval was concerned and scored as 1.

For verb accuracy coding, single-word verb responses matching the standard item name or a valid synonym carrying the same argumental structure (e.g., *cammina* “he/she walks” and *passeggia* “he/she strolls”) were scored as correct (1 point). Four error types were scored as incorrect (0 points): Type 1 – Omission (e.g., “I don’t know”); Type 2 – Syntactic category errors (non-verb responses such as nouns or adjectives); Type 3 – Semantic related responses (e.g., *beve* “he/she drinks” for *brinda* “he/she toasts”); Type 4 – Image-decoding errors (e.g., *balla* “he/she dances” for *sviene* “he/she faints”). Additionally, after discarding all error-bearing responses, we annotated three correct response types (1 point): Remark 1 – Tense (responses in all tenses other than present); Remark 2 – Descriptive additions (e.g., *cade dalla bici* “he/she falls off his/her bike” for *cade* “he/she falls”); Remark 3 – Circumlocutions (e.g. *fa un muro* “he/she makes a wall” for *costruisce* “he/she builds”).

A qualitative analysis of error types was also conducted (see Sections 6.3.1 *Accuracy in Noun Picture Naming* and 6.3.3 *Accuracy in Verb Picture Naming*).

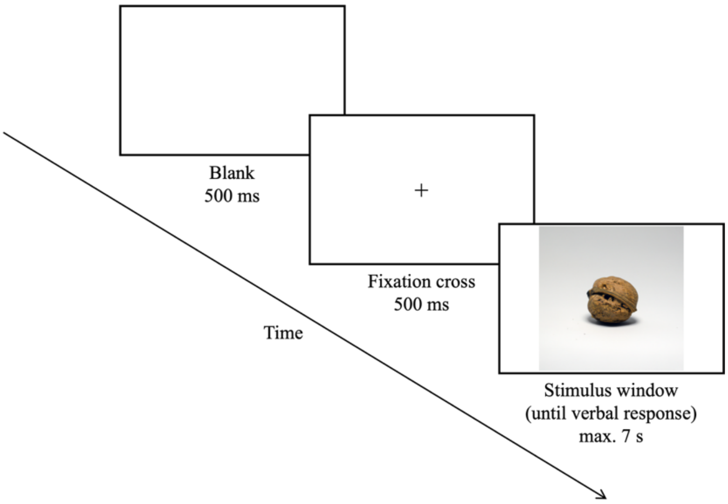


Figure 11. Experimental Procedure

6.2 Statistical Analysis

All analyses were conducted in R (version 4.4.2). We used the Shapiro-Wilk test to assess the distribution of accuracy and reaction time data.

6.2.1 Accuracy Analysis

To analyse naming accuracy, we fitted separate mixed-effects logistic regression models (package *lme4*) for nouns and verbs. Accuracy was treated as a binary dependent variable (correct = 1; incorrect = 0).

For nouns, we included group, linguistic category, and action-relatedness ratings as fixed effects. Log-transformed word frequency, word length, and picture goodness were included as z-scored covariates. Participant ID and item were included as random intercepts to account for subject and item-level variability.

To determine the best-fitting model, we followed a stepwise simplification procedure, beginning with a model including all main effects and interactions (*group* x *category* x *action-relatedness*). This model was compared to nested models with fewer interaction terms using likelihood ratio tests and the Akaike Information Criterion (AIC). A difference in AIC of at least 2 points was considered meaningful for model selection. Exploratory post hoc comparisons were performed using interaction models, regardless of the overall significance of interaction terms, and *p*-values were adjusted using Bonferroni correction to control for multiple comparisons.

For verbs, the same modelling structure was applied, with the addition of agentivity (agentive vs. non-agentive) as a fixed effect. Interaction terms including agentivity were evaluated during model comparison. Post hoc comparisons were conducted using interaction models, with Bonferroni-adjusted *p*-values.

6.2.2 Reaction Time Analysis

For the analysis of reaction times, only correct trials were considered. Reaction times were log-transformed to reduce skewness and analysed separately for nouns and verbs by fitting linear mixed-effects models (package *lmerTest*).

For nouns, the model was fitted including group, linguistic category, and action-relatedness as fixed effects, with z-scored covariates (log frequency, word length, and picture goodness). Participant ID and item were included as random intercepts. As for accuracy, a stepwise model comparison was employed to evaluate interaction effects (*group* x *category* x *action-relatedness*), with likelihood ratio tests and AIC values for model selection. A difference in AIC of at least 2 was again considered meaningful. Pairwise post hoc comparisons were carried out using estimated marginal means (package *emmeans*) with Bonferroni *p*-values adjustment.

For verbs, the model structure mirrored that for nouns but included agentivity as an additional fixed effect. Interaction terms involving agentivity were tested during model comparison. Post hoc comparisons were performed as above, using estimated marginal means and Bonferroni correction.

6.2.3 Correlation Analyses

To explore the relationship between linguistic performance and clinical or cognitive measures, separate correlation analyses were conducted for accuracy and reaction times for both nouns and verbs. Naming accuracy and mean reaction times were correlated with clinical variables such as disease duration, motor severity scores (e.g., UPDRS III), and neuropsychological test performance (e.g., MoCA) using Spearman's rank correlations.

6.3 Results: Lexical Access Performance

We performed between-group comparisons on the outcome variables Accuracy and Reaction Times.

6.3.1 Accuracy in Noun Picture Naming

Descriptive statistics indicated high overall accuracy in both groups (HCM: *M* = 93.76%, *SD* = 4.08%; PD: *M* = 92.17%, *SD* = 4.41%). Group means and standard deviations for each semantic category are reported in Table 12 and visualised in Figure 12.

The final mixed-effects logistic regression model included fixed effects of group (PD, HCM), category (seven noun categories: shapes, naturals, tools, ready-to-eat food, hand-action food, tool-action food, artefacts), and action-relatedness ratings. Log-transformed word frequency, word length, and picture goodness were entered as covariates. Participant and item were included as random intercepts to account for subject- and item-level variability.

In this model, group was not a significant predictor of accuracy ($\beta = -0.303$, $p = .127$), nor was action-relatedness ($\beta = -0.307$, $p = .149$). The main effect of category significantly improved model fit compared to a model without this factor ($\chi^2(6) = 13.54$, $p = .035$), and several categories, "hand-action", "ready-to-eat", "tool-action", and "tools", differed significantly from the baseline level. Among the covariates, word frequency ($\beta = 0.692$, $p = .002$) and word length ($\beta = 0.672$, $p = .006$) showed a significant effect on accuracy, while picture goodness, the correspondence between each picture and the associated target word, did not reach significance.

Model comparisons indicated that adding interaction terms (group x category, group x action-relatedness) did not significantly improve the model's fit over the main-effects-only model ($p = .119$). Therefore, no interactions were retained in the final model. Although the group x category interaction was not statistically significant overall, exploratory pairwise comparisons using *emmeans* (based on the interaction model) revealed a significant difference between groups for the category "shapes" ($p = .021$, Bonferroni-adjusted), with higher accuracy in the HCM group.

Table 12. Accuracy in Noun Picture Naming

Category	PD (*M* ± *SD*)	HCM (*M* ± *SD*)
Shapes	88.48 ± 13.51	94.54 ± 8.63
Naturals	86.66 ± 12.20	86.13 ± 13.84
Tools	97.70 ± 5.34	99.16 ± 3.41
Ready-to-eat	94.93 ± 7.87	97.06 ± 5.86
Hand action	97.24 ± 5.74	97.90 ± 6.22
Tool action	96.78 ± 7.10	99.16 ± 3.41
Artefacts	83.41 ± 13.35	82.35 ± 15.35
Overall accuracy	92.17 ± 4.41	93.76 ± 4.08

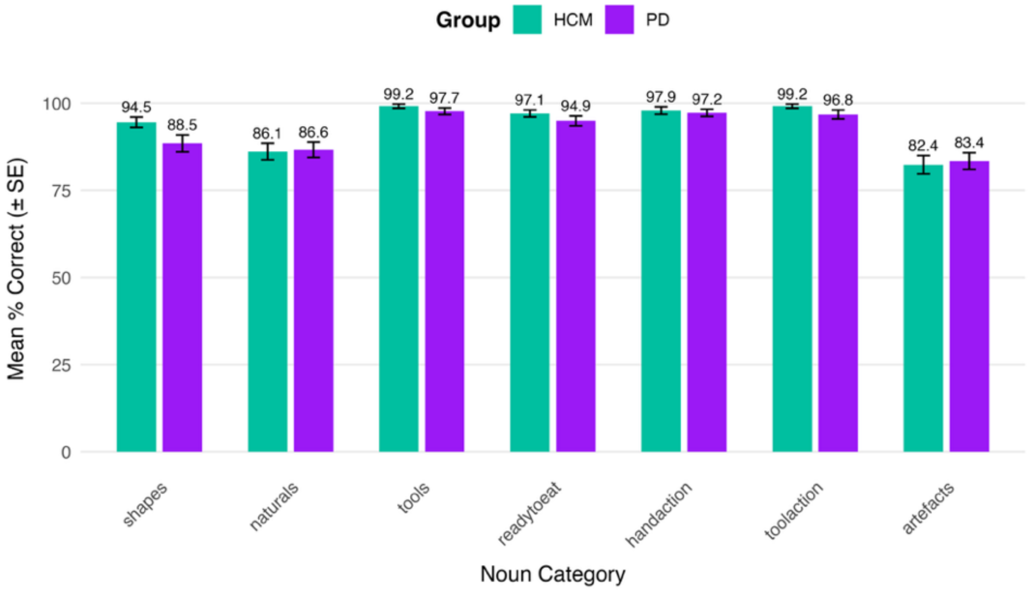


Figure 12. Percentage of Accurate Trials by Group and Noun Category

A qualitative analysis of the distribution of errors in noun naming was also conducted and summarised in Figure 13. Across groups, the majority of noun-naming errors consisted of semantic-relation errors, which accounted for 68% of errors in the HCM group and 59% in the PD group. These included responses related in meaning to the target, such as *macedonia* ("fruit salad") for *minestra* ("vegetable soup") or *oasi* ("oasis") for *deserto* ("desert"). Superordinate responses were the second most common error type (HCM: 22%; PD: 23%) and involved broader category labels, for example *indicazione* ("indication") for *freccia* ("arrow"). Other error types occurred infrequently in both groups. Syntactic-category errors (e.g., producing a verb instead of a noun, *firmare* "to sign" for *firma* "signature"), proper-name substitutions (e.g., *Sahara* for *deserto* "desert"), omissions, and image-decoding errors (e.g., *tavola* "table" for *quadrato* "square") each accounted for only a small proportion of responses (≤ 4% in HCM; ≤ 11% in PD). Overall, the two groups showed a highly similar qualitative noun-naming error profile, dominated by semantic-relation and superordinate errors.

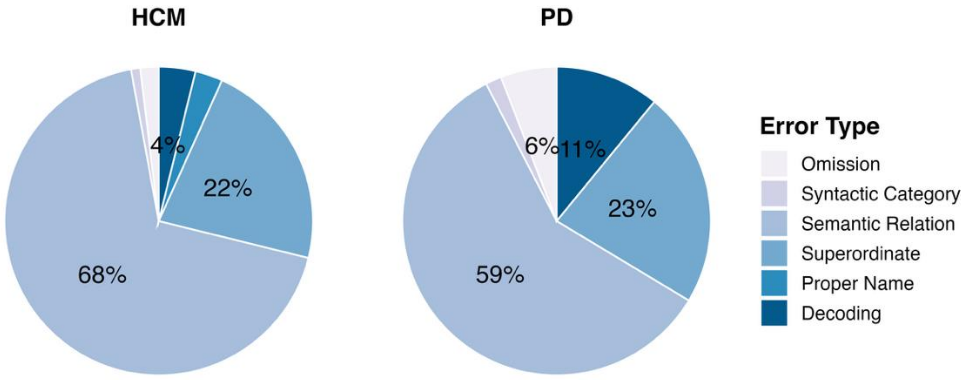


Figure 13. Distribution of Error Types in Noun Naming by Group

6.3.2 Reaction Times in Noun Picture Naming

In terms of latencies, a linear mixed-effects model with group (PD, HCM), category (seven nominal categories), action relatedness, and the covariates ($\log_{10}$ frequency, word length, picture goodness) as fixed effects, plus random intercepts for participant and item, showed a reliable group effect, with participants with PD producing slower responses than controls ($\beta = 0.243$, $SE = 0.048$, $t(100) = 5.06$, $p < .001$).

Model comparison (AIC/LRT) favoured a model featuring a *group* x *action-relatedness* interaction, which was the best at fitting the data. In this final model, the main effect of group remained significant ($p < .001$), there was no main effect of *action-relatedness* ($\beta = 0.046$, $SE = 0.037$, $p = .219$), but a significant *group* x *action-relatedness* interaction emerged ($\beta = -0.009$, SE = 0.004, $t(2800) = -2.42$, $p = .016$). This pattern indicates that, within the PD group only, reaction times decreased as action-relatedness increased, with *faster* responses for more actional items, whereas no comparable slope was evident in the control group (Figure 14). None of the low-level covariates (picture goodness, word frequency, or word length) reached significance (all $p > .19$).

Alternative models including a *group* x *category* interaction yielded main effects of both group and category but no significant interaction terms, suggesting that the cost in reaction times for PD is not modulated by nominal category. Such interaction did not improve fit over the final model (ΔAIC < 2).

To further explore group differences across semantic categories, we conducted *post hoc* comparisons on *group* x *category* using the full three-way interaction model. Applying a Bonferroni correction for seven comparisons (threshold: 0.0071, 0.05/7 comparisons), a significant group difference was observed for the category "artefacts" ($p = .005$), with PD participants responding slower than controls. The difference in "toolaction" ($p = .008$) was marginal, narrowly missing the corrected significance threshold, while an initially detected difference in "shapes" ($p = .0382$) did not survive correction for multiple comparisons. All other categories showed no reliable group differences after correction.

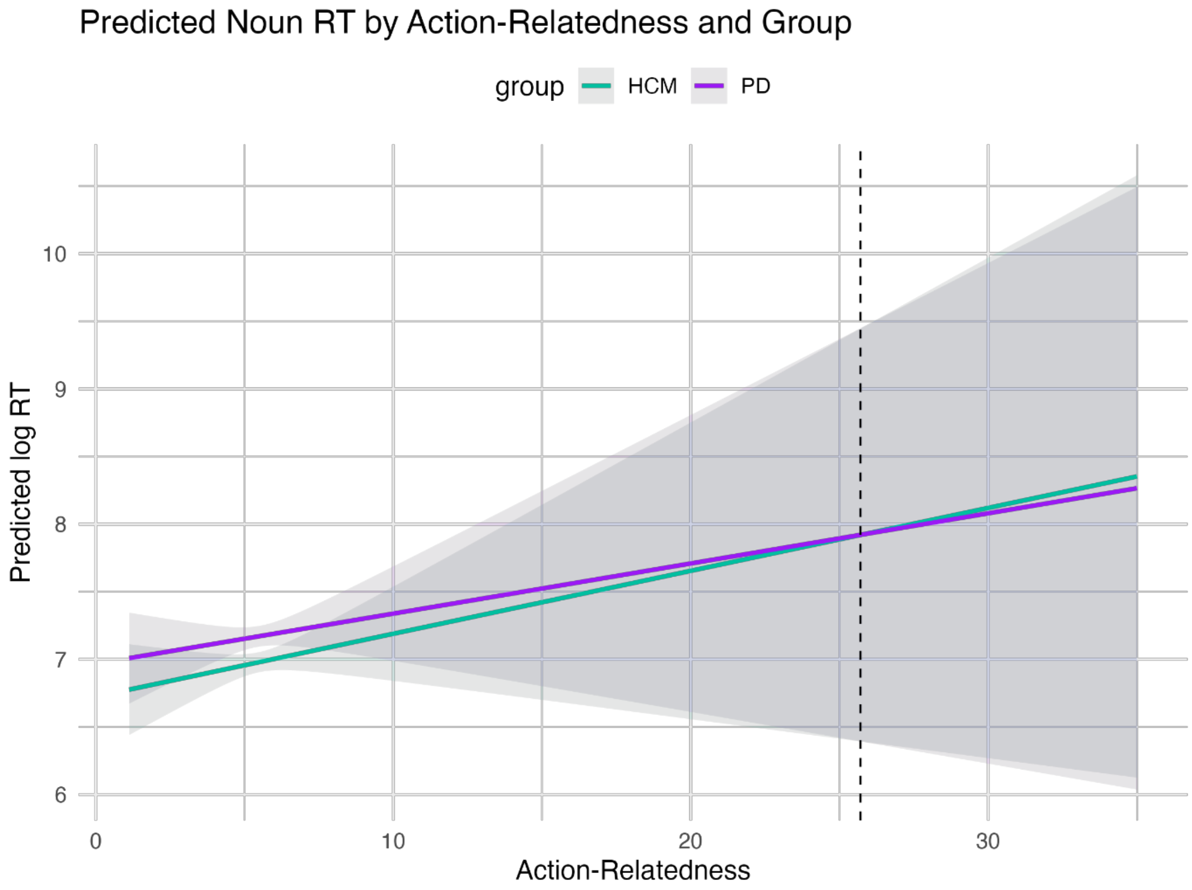


Figure 14. Faster responses for more actional items in PD, no comparable slope in HCM

Note. Shaded areas represent 95% confidence intervals (CI) around the predicted mean log RT from the linear mixed-effects model. The x-axis shows action-relatedness of nouns (higher values indicate greater action-relatedness). The dashed vertical line shows the predicted crossover point between PD and HCM groups (predicted beyond observed data range).

6.3.3 Accuracy in Verb Picture Naming

Descriptive statistics indicated overall high accuracy for verb naming in both groups (HCM: $M = 77.23\%$; $SD = 8.94\%$; PD: $M = 72.92\%$; $SD = 11.09\%$). Group means and standard deviations for each verbal category are reported in Table 13 and visualised in Figure 15.

The final mixed-effects logistic regression model included fixed effects of group (PD, HCM), category (five verb categories, namely: transitive accomplishments, transitive achievements, unaccusatives, unergatives, unergatives with internal agentivity), action-relatedness ratings, and the psycholinguistic covariates $\log_{10}$ frequency, word length, and picture goodness. Participant and item were entered as random intercepts to account for between-subject and between-item variability.

In this final model, group was not a significant predictor of accuracy ($\beta = -0.210$, $p = .112$) when controlling for the linguistic covariates. Neither category nor action-relatedness reached significance (all $p > .10$), and none of the psycholinguistic covariates showed significant effects (all $p > .12$).

Model comparison using likelihood ratio tests and AIC values indicated that adding interaction terms such as *group* x *category*, *group* x *action-relatedness* did not improve model fit (all $p > .10$). Similarly to nouns, model comparisons favoured the main-effect-only model also for verbal accuracy, since the addition of interaction terms did not significantly improve the model fit.

To explore potential effects of agentivity, we also tested a model including the *group* x *agentivity* interaction. While there was a numerical trend for reduced accuracy on non-agentive verbs across groups ($\beta = -1.759$), the interaction with group was not significant ($p = .88$), suggesting that PD participants were not differentially affected by verb agentivity relative to control.

Taken together, the final model did not reveal any significant effect of group, category, or action-relatedness on verb naming accuracy.

Table 13. Accuracy in Verb Picture Naming

Category	PD ($M \pm SD$)	HCM ($M \pm SD$)
Transitive (accomplishment)	76.50 ± 15.89	80.09 ± 11.26
Transitive (achievement)	52.07 ± 21.04	57.14 ± 18.21
Unaccusative	67.10 ± 23.41	75.15 ± 20.02
Unergative	91.24 ± 10.87	94.37 ± 7.94
Unergative (internal agentivity)	76.04 ± 16.65	78.79 ± 16.41
Overall accuracy	72.92 ± 11.09	77.22 ± 8.94

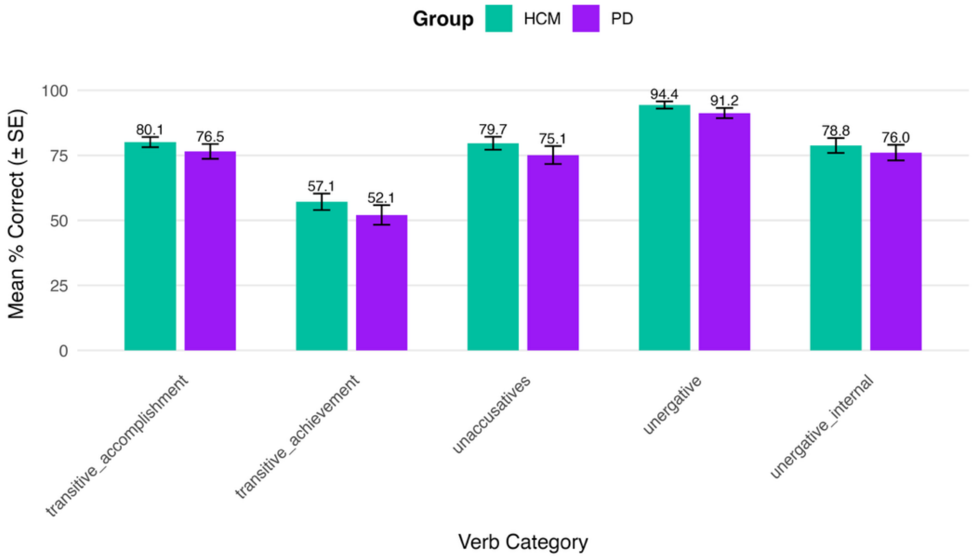


Figure 15. Percentage of Accurate Trials by Group and Verb Category

A qualitative analysis of the distribution of errors in verb naming was also conducted and summarised in Figure 16. Across groups, verb-naming errors were predominantly semantic-relation errors, which accounted for 49% of errors in the HCM group and 37% in the PD group. Decoding errors were the second most frequent type in HCM participants (28%) and remained frequent in the PD group (25%). Syntactic-category errors were more common in PD (31%) than in HCM (18%), whereas omissions were relatively rare in both groups (HCM: 5%; PD: 8%). Overall, the two groups showed a broadly similar qualitative verb-naming error profile, dominated by semantic-relation and decoding errors, and with PD participants producing more syntactic-category errors (i.e., non-verb responses).

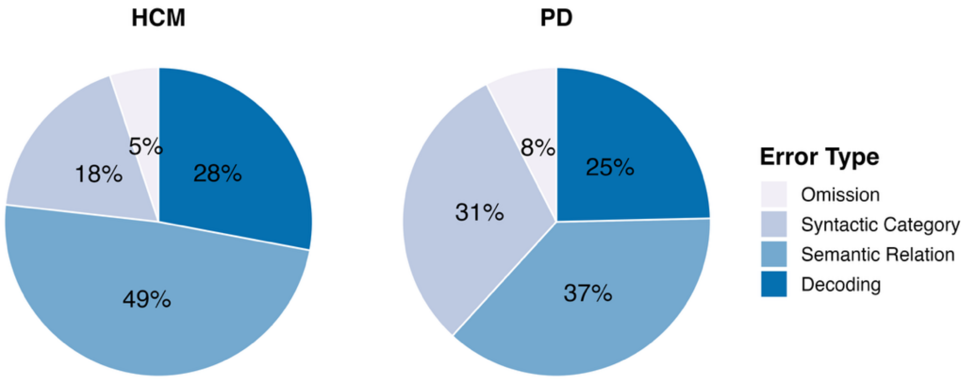


Figure 16. Distribution of Error Types in Verb Naming by Group

6.3.4 Reaction Times in Verb Picture Naming

Regarding reaction times, a linear mixed-effects model with group (PD, HCM), category (five verbal categories: transitive accomplishments, transitive achievements, unaccusatives, unergatives, unergatives with internal agentivity), action-relatedness, and covariates ($\log_{10}$ frequency, word length, picture goodness) as fixed effects, plus random intercepts for participant and item, was fitted to the verb data.

Participants with PD produced overall slower responses than controls ($\beta = 0.308$, $SE = 0.185$, $t(1470) = 1.66$, $p = .097$). Model comparisons (AIC/LRT) indicated that including the three-way interaction between group, category, and action-relatedness significantly improved model fit ($p = .025$), suggesting that differences in reaction times are modulated by both linguistic and conceptual features. We also examined whether verbal agentivity (agentive vs. non-agentive) modulated reaction times and whether it interacted with group. Adding agentivity, either as a main effect or in interaction with group, did not significantly improve the model fit (all $p > .28$). Therefore, agentivity was not retained in the final model.

Pairwise comparisons revealed that PD participants were slower than controls across all verb categories. However, after applying a Bonferroni correction for five comparisons (threshold: 0.01, 0.05/5 comparisons), significant group differences remained for “transitive accomplishments” (*scrive* ‘she writes’, *gonfia* ‘he blows’, *disegna* ‘she draws’, *cucina* ‘she cooks’, *costruisce* ‘he builds’, *attraversa* ‘he crosses’, *taglia* ‘he cuts’, $\beta = -0.228$, $p = .0003$), “unergatives” (*brinda* ‘he toasts’, *bussa* ‘he knocks’, *cammina* ‘she walks’, *nuota* ‘he swims’, *pattina* ‘he skates’, *prega* ‘she prays’, *scia* ‘he skis’, $\beta = -0.211$, $p = .0006$), and “unergatives with internal agentivity” (*dorme* ‘he sleeps’, *tossisce* ‘he coughs’, *vomita* ‘she vomits’, *trema* ‘he trembles’, *sbadiglia* ‘she yawns’, *ride* ‘he laughs’, *piange* ‘she cries’, $\beta = -0.300$, $p = .0003$). Differences for “transitive achievements” (*arresta* ‘she arrests’, *vince* ‘she wins’, *buca* ‘he pops’, *trova* ‘he finds’, *imbuca* ‘he posts’, *scopre* ‘he discovers’, *para* ‘he saves’, $\beta = -0.171$, $p = .013$) and “unaccusatives” (*sviene* ‘she faints’, *scivola* ‘he slips’, *esce* ‘she exits’, *entra* ‘she enters’, *cade* ‘he falls’, $\beta = -0.338$, $p = .017$) were at trend level and did not survive correction (Figure 17). These results indicate that verb naming was slower in PD overall, and the magnitude of slowing was modulated by verb type, with significantly lower performance in transitive accomplishment, unergatives and unergatives with internal agentivity. No significant group x action-relatedness interaction emerged independently of category.

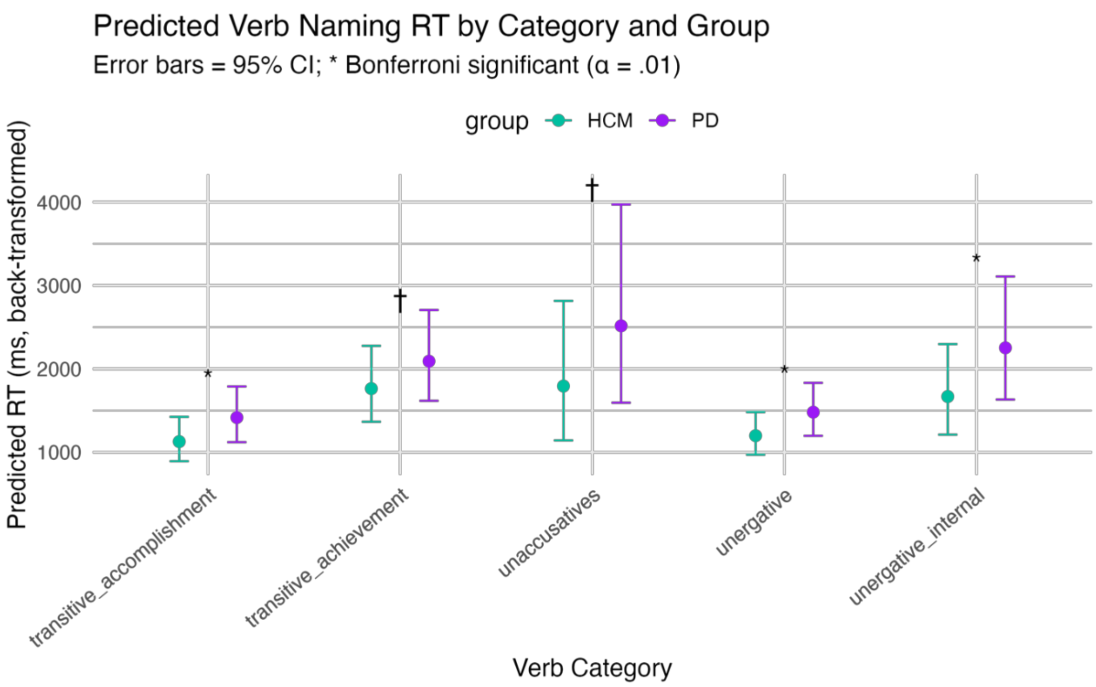


Figure 17. Predicted reaction times in verb picture naming by category and group

Note. * indicates a Bonferroni-corrected significant difference between PD and HCM (*p* < .01); † indicates a trend-level difference (*p* < .05, uncorrected).

6.3.5 Correlations with Clinical and Neuropsychological Variables

For the PD group, we performed Spearman's rank correlations between naming performance (accuracy and reaction times) and the following clinical variables: age at onset, disease duration, UPDRS I, UPDRS II, UPDRS III, Hoehn & Yahr score, L-Dopa equivalent daily dose (LEDD), and dopamine agonist L-Dopa equivalent daily dose (DA_LEDD). Categorical variables, namely phenotype and most-affected side, were analysed using Wilcoxon rank-sum tests. We then applied Benjamini–Hochberg correction to adjust for multiple comparisons.

A strong and significant positive association was found between noun naming reaction times and age at onset (r = 0.556, *p*_adj = 0.012), indicating that patients with later disease onset tended to name nouns more slowly. Noun naming reaction times were also found to be significantly negatively associated with DA_LEDD (r = -0.469, *p*_adj = 0.036), suggesting that higher dopamine agonist dosage may be linked to faster responses in noun naming.

Positive correlations between verb reaction times and UPDRS III (motor symptoms severity) and Hoehn & Yahr scores (disease stage) were moderate and nominally significant (r = 0.433, *p* = 0.017 and r = 0.418, *p* = 0.021, respectively), meaning that people with PD with more severe motor symptoms named verbs more slowly. However, these associations did not survive multiple comparisons correction (*p*_adj = 0.086 for both). No other clinical associations survived correction.

For both PD and control groups, we then investigated correlations between naming performance and the following neuropsychological variables: FAB_1 (linguistically mediated executive function), FAB_2 (planning), FAB_3 (inhibition), FAB total, MoCA total score, anxiety, and depression.

For the PD group, noun accuracy was found to strongly positively correlate with MoCA score (r = 0.506, *p*_adj = 0.031), indicating that better global cognition was associated with higher noun naming accuracy.

In the HCM group, noun accuracy was significantly positively associated with FAB 2 (r = 0.435, *p*_adj = 0.047) and FAB total (r = 0.419, *p*_adj = 0.047). Noun reaction times in HCM were found to negatively correlate with MoCA scores (r = -0.529, *p*_adj = 0.009), indicating faster naming in individuals with higher global cognitive functioning.

Verb accuracy was found to significantly correlate with multiple neuropsychological measures in both groups. For the PD group, significant moderate to strong correlations were observed with FAB 1 (r = 0.479, *p*_adj = 0.017), FAB 2 (r = 0.466, *p*_adj = 0.017), FAB total (r = 0.515, *p*_adj = 0.017), and MoCA (r = 0.481, *p*_adj = 0.017), suggesting that better executive functions and global cognition supported more accurate verb naming. For the HCM group, verb accuracy correlated strongly with FAB 1 (r = 0.539, *p*_adj = 0.008) and moderately with FAB total (r = 0.421, *p*_adj = 0.038) and MoCA (r = 0.416, *p*_adj = 0.038). No other correlations survived corrections.

6.4 Discussion

This study assessed lexical retrieval in individuals with PD and in matched healthy controls (HCM) using a picture-naming paradigm designed to disentangle the respective contributions of conceptual (action-relatedness) and linguistic (argumental or qualia structure) dimensions to lexical access. A central and novel finding of this work is that the lexical access deficit observed in PD, affecting both nouns and verbs, albeit with partially distinct patterns, is not generalised, but rather shows a strong interaction with the underlying linguistic and conceptual structure of the stimuli. By analysing both accuracy and reaction times, this work provides a more comprehensive account of lexical processing dynamics in PD, going beyond correctness to examine the temporal efficiency of access and retrieval mechanisms. To the best of our knowledge, all previous studies assessing lexical access in PD through picture naming used accuracy as the primary outcome measure, either in terms of correct responses (Bocanegra et al., 2015; 2017, Cotelli et al., 2007, Herrera et al., 2012, Johari et al., 2019a, Salmazo-Silva et al., 2017) or as error patterns (Aiello et al., 2022a). Our study is the first to analyse both accuracy and reaction times, with the intent of obtaining a more global understanding of the processes of lexical access in PD, especially considering that time is a crucial component of lexical retrieval and captures phenomena that might escape when considering accuracy alone. It should be noted that previous studies do not always report their accuracy coding choices. Therefore, direct comparisons with previous studies are made less straightforward. Our accuracy coding choices are fully reported in the “Procedure” section and partially resemble those by Salmazo-Silva et al. (2017).

6.4.1 Accuracy Patterns

Accuracy was overall high across groups and parts of speech, suggesting preserved lexical-semantic representations in PD. As for noun naming, the only reliable difference emerged in the “shapes” (qualia) category, where PD participants were less accurate than controls. A qualitative inspection of errors revealed that many incorrect responses in this category largely stemmed from difficulties in picture interpretation, with participants responding “painting” instead of *square* or “egg” instead of *oval*, rather than lexical deficits *per se*. These tendencies may reflect a set-shifting difficulty, a reduced ability to adapt to less typical lexical categories, consistent with executive dysfunctions commonly reported in PD. In fact, the stimulus set predominantly featured concrete, often food-related items. The abstract nature of the “shapes” stimuli may have conflicted with participants’ expectations, requiring a shift in the semantic set. No significant differences were observed for other categories or for action-relatedness, supporting the view that noun accuracy remains largely unaffected when perceptual and lexical confounds are controlled.

As for verb naming, accuracy was also comparable between groups once semantic and linguistic variables were accounted for. Although PD participants showed lower accuracy than controls, this difference did not persist in the final model, nor did agentivity or verbal category (argumental structure) significantly modulate accuracy. This finding indicates that core verb representations remain intact in PD. It also underscores that the principal group differences in lexical access likely manifest in processing speed rather than accuracy.

6.4.2 Reaction Times: Nouns

Reaction times provided a more sensitive index of lexical access efficiency. For nouns, PD participants were slower overall compared to matched neurotypical controls. Crucially, a significant interaction between group and action-relatedness emerged: within the PD group only, higher action-relatedness was associated with faster naming responses. This effect highlights not merely a general processing slowdown but a response pattern that interacts systematically with the linguistic and conceptual properties of the stimuli, indicating that lexical access difficulty in PD is far from uniform. This pattern suggests that action-related conceptual content may facilitate lexical retrieval in PD, contrary to earlier accuracy-based reports of impaired action-related processing (e.g., Bocanegra et al., 2015). One interpretation is that action-related concepts, which are more concrete and richly grounded in sensorimotor representations, remain relatively accessible in PD. Another explanation might be that people with PD are more sensitive than controls to action-related conceptual content, and a compensatory activation might be at play.

Additionally, exploratory category-level comparisons further revealed a specific slowdown for “artefacts”, a category encoding entities that are results of actions (e.g., *footprint*, *signature*, *wound*, *bite*, *shadow*, *embroidery*, *tattoo*). These items require integrating an implied causal structure, which means not only to understand the object itself but also the prior event or agent that produced it. Such inferred agentivity may increase cognitive load in PD, consistent with difficulties in activating internally generated or causally structured representations. Taken together, noun naming results suggest that direct action-related meanings may be preserved or even facilitative in PD, while indirectly agentive or causative meanings may pose greater challenges. Importantly, these results do not reflect a generalised slowing, nor a slowing specifically triggered by the conceptual feature of action-relatedness; rather, they reflect a slowdown tied to the *linguistic* variant of action-relatedness, particularly those structures that encode telicity and agentivity, such as “artefacts” in the Generative Lexicon. In other words, these findings allow us to separate the conceptual facilitation (action-related meanings supporting retrieval) from linguistic impairment (structure slowing it), revealing a notable and previously covert graded dissociation.

6.4.3 Reaction Times: Verbs

For verbs, across all categories, PD participants showed slower naming latencies than controls, even when controlling for lexical and perceptual covariates. Model comparisons supported a group x category x action-relatedness interaction, indicating that the degree of slowing varied across verb types and was modulated by their conceptual motion content. Post hoc analyses revealed that PD participants were significantly slower for transitive accomplishments, unergatives, and unergatives with internal agentivity, even after Bonferroni correction. In contrast, transitive achievements and unaccusatives showed only trend-level group differences.

This pattern suggests that verb type and internal causality crucially influence lexical access in PD. The most affected categories, unergatives and unergatives with internal agentivity, involve internally caused or volitional actions, where the agent is intrinsic to the subject. In contrast, unaccusatives describe externally caused or spontaneous events (e.g., *to fall*, *to slip*), and transitive verbs explicitly encode an external agent acting on an object. The longer latencies observed in PD for internally caused actions may reflect deficits in simulating or activating agentive dynamics, especially when the source of causation lies within the subject itself. This notion is consistent with impaired motor representation and self-initiated action in PD.

Notably, agentivity as a formal variable (agentive vs. non-agentive) did not independently improve model fit, suggesting that the effect of agentivity might be contextual rather than categorical. In other words, difficulties arise not from agentivity *per se* but from how agentivity is linguistically encoded, specifically when embedded in certain argumental or thematic templates (e.g., unergatives, internally agentive verbs). As far as action-relatedness is concerned, it does not appear to be globally impaired, but becomes problematic when linguistically or conceptually embedded within complex causal structures. However, the structure of the dataset prevents us from fully disentangling the contribution of agentivity from that of verb category: agentivity levels are only partially crossed with argumental classes (e.g., [+m] occurs exclusively in "unergative_internal" verbs, while [-c-m] occurs only in a subset of unaccusatives), creating a nested distribution that limits independent estimation of agentivity effects. As a result, a role for agentivity cannot be ruled out, but it cannot be statistically confirmed either, since any apparent influence of internal agentivity remains confounded with the argument-structure properties of the specific verb classes.

6.4.4 Integrating Noun and Verb Findings

Together, the results across word classes point to a nuanced account of lexical access in PD. Nouns and verbs, however, contribute to this picture in partially different ways. The deficit is not a uniform action-semantic impairment but appears modulated by how agentive or action-related information is represented and accessed within linguistic structures. For nouns, the pattern is particularly clear: action-relatedness at the conceptual level facilitates retrieval in PD, whereas the linguistic encoding of causation and agentivity (as in "artefacts") selectively slows naming. For verbs, in contrast, group differences emerge primarily in reaction times for specific argument-structure classes, with no independent contribution of action-relatedness or agentivity once category is taken into account, and with agentivity effects remaining statistically inseparable from verb type. Participants with PD perform normally or even show facilitation when action-related meanings are direct and externally observable (e.g., *to cut*, *to build*, *hammer*, *walk*), but exhibit disproportionate slowing when such meanings are implicit, internalised, or causally inferred (e.g., *to fall*, *to tremble*, *footprint*). This pattern aligns with models proposing that PD involves a reduced capacity for generating internally driven representations (Jeannerod, 2006; Boulenger et al., 2008), extending this principle to the lexico-semantic domain.

From a linguistic perspective, these results suggest that conceptual and structural complexity interact during lexical retrieval. In the nominal domain, this interaction emerges as a relatively sharp dissociation between beneficial action-relatedness and costly linguistic realisation of causation, whereas in the verbal domain it appears associated with some argumental templates, particularly those that tend to encode internal or subject-intrinsic causality, even though agentivity cannot be cleanly isolated from category. When a lexical entry encodes causal or intentional features (the agentive *quale* in nouns; [+c+m] features in the verbal subject), its retrieval requires activating both event structure and thematic role mapping. This slower access observed in PD for internally agentive verbs and artefactual nouns therefore likely reflects difficulties integrating linguistic templates that embed causality, rather than a general semantic deficit, with nouns providing a clearer conceptual-linguistic dissociation and verbs offering converging, though more indirect, evidence of the same underlying vulnerability.

6.4.5 Clinical and Cognitive Correlates

Correlations with clinical and neuropsychological measures support this interpretation. In PD, slower naming latencies correlated with later disease onset and lower dopaminergic medication dosage, indicating that lexical access efficiency is partially modulated by dopaminergic availability. Additionally, correlations between naming accuracy and executive and cognitive measures (FAB, MoCA), further suggest that executive control contributes to efficient lexical selection, particularly for verbs, whose retrieval requires stronger morphosyntactic integration.

6.5 Summary and Conclusions

Overall, this study provides novel evidence that lexical-semantic access in PD is jointly modulated by both the conceptual (action-relatedness) and the linguistic (argumental and qualia) dimensions, and that these effects primarily manifest in the reaction times of their naming performance.

Among the limitations of this study, two items had to be excluded from the analyses: *salire* “to go up” and *scendere* “to go down” were originally classified as “unaccusatives”. However, the images used to represent them depicted stairs, and this specific visual context is likely to have activated the transitive/agentive interpretation of these verbs, rather than the intended unaccusative reading. Despite this shortcoming, which might have reduced the statistical power for that verbal category, the results showed that PD participants were slower to retrieve verbs and nouns requiring implicit agentive or causal reasoning, but not those involving direct, externally observable actions. These findings suggest that lexical access difficulties in PD do not emerge from a global impairment in processing action semantics, which is the prevalent view in previous literature, but from a selective vulnerability of linguistically mediated representations of causation and agency. This supports the view that PD affects the integration of conceptual and linguistic information during lexical retrieval, a process dependent on implicit causality and higher-order linguistic control. Chapter 7 examines deverbal nouns with a morphological derivation task to determine whether the PD-related difficulties identified here arise from conceptual factors, morphosyntactic factors, or an interaction between the two. By testing how action-relatedness and morphosyntactic complexity modulate access to derived forms, the next chapter provides an essential extension of the present findings and allows a more precise localisation of the locus of impairment.

Chapter 7 – Morphological Competence in Parkinson's Disease (Study 2)

7.1 On Nominalisation and Deverbal Nominals

Nominalisation refers to the process (and the result of that process) of "turning something into a noun" (Comrie & Thompson, 1985). In the history of nominalisation literature, both lexicalist and syntactic accounts on word formation and nominalisation have been put forward. The former approach assumes that operations take place over word stems and generally involves grammatical underspecification of lexical items (Chomsky, 1970). Instead of being either nouns or verbs, lexical entries are category-neutral, and the lexicon has a syntax-independent generative system deputed to word formation. The latter perspective maintains that words are derived in the syntax (Lees, 1960). The different theoretical approaches have tried to capture the complexity of nominals, which constitute a heterogeneous class (Alexiadou & Grimshaw, 2008).

In the present work, we will deal with one nominalisation type, namely deriving nouns from verbs. The nouns resulting from such a nominalisation process are called "deverbal action nominals". Deverbal nominals are often regarded as a hybrid category. In fact, despite being nominal structures, they preserve some verbal features in their morphology, syntax, and semantics.

7.1.1 Morpho-Syntactic and Semantic Features of Deverbal Nominals

Deverbal nominals are complex nouns derived by affixation or by conversion (zero-affixation) as opposed to simplex nouns, which are underived. Here are some examples of deverbal nominals from Lieber (2017): *writing*, *destruction*, *refusal*, *amusement*, *driver*, *employee*, *certainty*, *happiness*, *childhood*, *kingdom*, *hipster*, *mountaineer*, *trashmeister*, *kick*. Given the variety of such structures, there are many possible classifications. One hinges on their argument structure (Grimshaw, 1990) and will be tackled in the next section. Nevertheless, it is essential to point out that an interpretation-based classification is also possible. From the examples above, *driver* can be ascribed to the category of "agent" or "instrument nominal", *employee* is a "patient nominal", *kingdom* can have a "location" reading. However, the most frequent nominal structure is that of "action nominals", like *destruction* and *refusal* (Melloni, 2011).

The hybrid status of deverbal nominals has been given a multitude of possible explanations (only a few will be mentioned here). In Chomsky's *Remarks* (1970), morphology and syntax are kept apart in the nominalisation process to the point that the pair *destroy*/*destruction* corresponds to "DESTROY", one category-neutral entry of the lexicon, which acquires its syntactic category once it is collocated in an X' schema, as illustrated in (1).

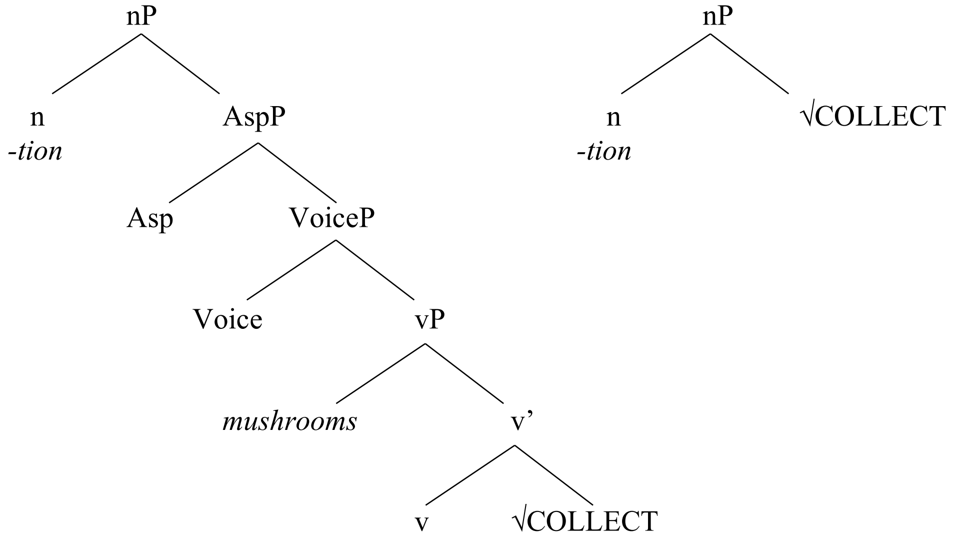
A later approach, which instead supports the integration of morphological processes and syntax, is the Distributed Morphology (DM) framework (Halle & Marantz, 1993). Word formation and syntax are incorporated in the same component of grammar (Alexiadou, 2001; Marantz, 1997) instead of being kept apart. Meaning itself is not a property associated with lexical items, but the syntactic structure largely determines it. In DM, syntax operates on category-neutral roots (e.g., √DESTROY), which are combined with functional heads of the *v* or *n* type (Marantz, 1997), as illustrated in (2). Whether nominalisation must be considered a lexicalist or a syntactic phenomenon is still an open issue.

(1)

(2)

Returning to some semantic considerations, one of the key features characterising all types of nominalisations is the polysemy phenomenon (Melloni, 2011): some deverbal nouns can refer to both events and results, and the context determines which one. For example, *collection* can refer to both the act of collecting something and the result of that collection act. This systematic Event / Result ambiguity has been the focus of research in this area, and this nominalisation hallmark has been used to elucidate the morphosyntactic features of deverbal nominals. Alexiadou (2001) points out that nouns denoting complex events and nouns denoting results (more on these in the next section) should have different structures, as only the former type bears verbal structure and related arguments (3):

(3)


Complex Event Nominal

Result Nominal

On the other hand, the systematic ambiguity between Event and Result readings might suggest that the different readings should come from the same structure (cf. Melloni 2010, p. 163).

7.1.2 Towards a Typology of Readings for Deverbal Nominals

In an attempt to outline a typology for deverbal nominals, Grimshaw (1990) represents a mandatory reference. In particular, her tripartite distinction between nominals denoting Complex Events (CEN), Simple Events (SEN), and Results (RN) is justified by their different semantic and morpho-syntactic behaviour, especially in regard to their argument structure (henceforth, A-structure):

- Complex Event Nominals (CENs): denote events and mandatorily take arguments.
  Example: "The *construction* of the house (by the company)";
- Simple Event Nominals (SENs): denote events but cannot take arguments.
  Example: "The *race* (took place at noon)";
- Result / Referential Nominals (RNs): denote entities/objects and cannot take arguments.
  Example: "The *construction* (*of the house) is huge".

The fundamental difference between these three types is that the lexical entries of CENs (but not those of SENs and RNs) inherit their A-structure from the verb and display verbal-like argument-taking abilities and necessities (to satisfy their A-structure requirements).

In fact, it seems that deverbal nominals can be split into more than only three categories. In particular, there are several types of RNs, and the category of Simple State Nominals (SSNs) should also be considered alongside SENs, as nominalisation of verbs can concern both events (dynamic situations, e.g., *suspend → suspension*) and states (non-dynamic situations, e.g., *admire → admiration*). A recent account of the typology of deverbal nominals is given by Wood (2023) and takes into account these additional refinements that can be summarised with the following graph (Figure 18; Wood, 2023, p. 18):

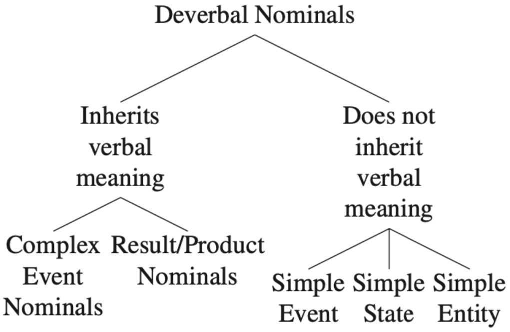


Figure 18. Typology of Deverbal Nominals according to Wood (2023)

According to this account, it is possible to identify (1) CENs, carrying the identical meaning of the verb but syntactically behaving like a noun; (2) RNs, referring to entities that exist as a result of the event encoded by the verb; (3) SENs, in which the *n* head independently refers to an event, without inheriting this meaning by the verb; (4) States, similar to (3) but with *n* denoting a state; (5) Entities, similar to (3) but with *n* denoting a concrete entity.

7.1.3 Notes on the Syntax of Deverbal Nominals in Italian

One of the ways in which deverbal nouns can be derived in Italian is by a *suffixation* process of verbs. Additional ways are *conversion*, yielding to deverbal nominals starting from the present tense, such as the masculine *arrivo* "arrival" and the feminine *ricerca* "search", and nominalisations from non-finite forms of the verb (e.g., *Infinito Sostantivato, il legger libri tutte le sere*, "reading books every evening"). However, both conversion and nominalised infinitives are far less productive in Italian and often display lexicalised behaviour, making them less suitable for the fine-grained morpho-syntactic analysis pursued here.

Only deverbal nouns obtained by suffixation will be considered hereafter, because they represent the most productive type of nominalisation in Italian and show the clearest morphological reflex of derivation. Unlike formations obtained through conversion or through nominalised infinitives, suffixal nominalisation exhibits overt morphological marking. The most productive suffixes are -*mento*, -*zione*, and -*tura* (Gaeta & Ricca, 2006). Event nominals of this type are termed *transpositional*, as they involve a shift of the verbal meaning into a nominal lexical item (Melloni, 2011). The obtained nominals (4b) preserve the semantic and grammatical features of the base verb (4a), such as its A-structure:

(4)	a.	Il	pilota	**ha**	**cambiato**	direzione			
			A	AUX	change-PTCP	P			
		"The pilot changed direction"							
	b.	Il	**cambia-mento**	di	direzione	da	parte	del	pilota
			change-NMLS		P				A
		"The change of direction by the pilot"							

In Grimshaw's terminology (1990), the abovementioned case falls within the CENs category. There are morphologically simple nouns, like *festa* "party", *gara* "race", *matrimonio* "wedding", which also denote events and can be identified by using several diagnostics having to do with eventhood. At the same time, they do not licence agentive *by*-phrases like the one in (4b). These correspond to Grimshaw's SENs. As concerns RNs, they do not denote events but entities (for a much more detailed taxonomy, see Melloni, 2011, p. 132).

7.1.4 Deverbal Nouns in Pathology: Why Are They Relevant? Rationale

Deverbal nominals simultaneously bear properties of nouns, grammatically behaving as such, and properties of verbs, inherently carrying verbal semantics. In particular, deverbal nominals of the "CENs" type in Grimshaw's classification encode a rich eventive and argumental structure, which includes causation and agentivity. This hybrid status makes them especially suitable for probing the interface between conceptual and linguistic structure.

As shown in Chapter 6, lexical access in PD is not uniformly impaired, but it is selectively modulated by how action-relatedness, causation, and agentivity are linguistically encoded. Nouns and verbs that required integrating implicit causal or agentive structure (e.g., artefacts as results of actions, internally agentive or unergative verbs) produced disproportionate slowing in PD. These findings suggest that PD does not primarily disrupt action semantics *per se*, but rather the integration of event structure and thematic-role information within the linguistic system.

Deverbal nominals offer a natural extension of this question. By definition, they are derived from verbs and often preserve key verbal properties such as event structure and A-structure, while at the same time belonging to the nominal system. They therefore provide an ideal testing ground to ask whether the PD-related vulnerabilities identified in Chapter 6 extend to the morphological derivation domain: do people with PD have difficulties when they must access or manipulate the verbal eventive core encoded inside these nominal forms?

A further aim of this investigation is to assess how deverbal nominals can contribute to shedding light on phenomena that hinge on the separation between these two categories, such as the so-called noun-verb dissociation which has been a frequent focus in the clinical literature. This phenomenon, attested in clinical linguistics, has been reported in patient studies demonstrating that some populations (e.g., aphasic patients) show selective deficits for one or the other category. However, this dissociation partially escapes researchers' understanding. In particular, it is not clear whether the nature of such dissociation has to be understood as a grammatical or a semantic one. Research in this area can benefit from the hybrid status of deverbal nominals, which might be helpful in elucidating the underlying mechanisms of language impairment in clinical populations.

7.1.5 Lexical Competence on Nouns and Verbs in PD: Is there a Dissociation Phenomenon?

A rich amount of research on linguistic impairment in PD has been devoted to lexical semantics. In the track of aphasiology tradition, the opposition between nouns and verbs has often been referred to as a dissociation phenomenon also in the case of PD (Bertella et al., 2002). However, it is evident that the lexical impairment in PD departs from that observed aphasia. In non-demented PD, it is not the whole category of verbs or the whole category of nouns exhibiting deficits. The *dissociation*, if we really want to stick to this terminology, is a more subtle one, thinning out the neat distinction between grammatical categories.

Two main domains have been tested in the PD literature concerning lexical competence, namely: lexical access, operationalised by picture naming and lexical decision tasks, and semantic knowledge, tested by means of semantic association and semantic similarity judgment tasks. In these domains, results tend to exclude a generalised impairment affecting the whole syntactic category. Instead, patients seem to manifest a sensitivity towards certain semantic properties of the verbal and nominal stimuli they are exposed to. As discussed in Chapter 2, the key feature in the case of nouns seems to be manipulability. PD patients exhibit impairments in naming objects with a high level of manipulability, such as “key” and “hammer”, and no impairment for objects with a low level of manipulability, such as “wall” and “mountain” (Bocanegra et al., 2017; Johari et al., 2019a). Such results seem to advocate for embodied cognition theories, which state that cognitive and language-related processes have their roots in body experiences, such as perception and action (Lakoff & Johnson, 1999; Barsalou, 1999, 2008). A study by Cotelli and colleagues (2007) has found a PD disadvantage compared to controls in naming all nouns, regardless of their level of manipulability. However, in this same study patients also showed an impairment for the class of verbal stimuli, suggesting a more generalised impairment. As for verbs, several semantic domains have been found to play a role in naming and semantic tasks. In particular, the degree of motion content encapsulated by the verb seems to be fundamental, with high-motion verbs like “to swim” and “to dig” being more difficult than low-motion verbs, like “to read” and “to sleep” (Herrera et al., 2012; Bocanegra et al., 2017). Similarly, an effect of speed has been identified in similarity judgment tasks, with fast actions like “to run” being more difficult than slow actions like “to shuffle” (Speed et al., 2017). Importantly, if action verbs have been found impaired, abstract verbs like “to depend” and “to improve” seem to be spared (Fernandino et al., 2013a). Finally, contrary to previous results on motion content, a recent study by Aiello and colleagues (2022a) found no effect of action-relatedness in verbal processing, but an effect of argument-structure complexity.

A crucial point emerging from both the prior literature and the empirical findings of Chapter 6 is the need to clearly distinguish between three levels of analysis: (i) the categorical distinction between nouns and verbs, (ii) access to the conceptual system, including the action-relatedness property (encompassing manipulability for nouns and motion content for verbs), and (iii) access to the linguistic system or, more specifically, to the *interface* where morphosyntactic structure encodes conceptual content. Chapter 6 showed that lexical access in PD is not uniformly impaired: people with PD did not show a category-wide noun or verb deficit, nor a general impairment for action-related concepts, with difficulties emerging instead when conceptual properties (causation, agentivity) were mediated by linguistic templates, pointing to a selective vulnerability at the conceptual-morphosyntactic interface.

Chapter 7 (Study 2) builds directly on this insight, and is designed to disentangle these three levels of analysis. To this end, it addresses the following research questions, each one corresponding to the three levels of analysis outlined above:

1. Does the part-of-speech distinction between nouns and verbs modulate naming performance in PD? This question aims at further excluding that PD shows a true noun-verb dissociation once conceptual and morphological factors are controlled.
2. Does action-relatedness independently affect naming performance in PD? A selective impairment for items with high action-relatedness across categories would point to a deficit located in the conceptual system, irrespectively of morphosyntactic expression. This result would be in line with some previous studies but not with Study 1, which highlighted a significant contribution of the linguistic dimension.
3. Does the morphological complexity of deverbal nominals modulate naming performance in PD beyond conceptual content? If morphologically complex nominalisations (CENs, which encode causation and agentivity) yield disproportionate difficulty, this would indicate a vulnerability at the morphosyntactic-conceptual interface, echoing the pattern observed in Chapter 6.

Together, these questions allow us to assess whether PD-related difficulties stem primarily from conceptual factors, from morphosyntactic structure, or emerge specifically when conceptual content must be expressed through a particular morphosyntactic template, which would represent a hallmark of interface-level impairment.

7.2 Elicited Production Task

7.2.1 Stimuli

The task was a modified version of the “Noun and Verb Retrieval in a Sentence Context” (NVR-SC) task devised by Crepaldi et al. (2006). It was divided into two parts to target two domains relevant for the present study: (i) the interaction between part of speech and action-relatedness (Part 1), and (ii) the role of morphological complexity in nominal derivation (Part 2).

7.2.1.1 Syntactic Category and Action-Relatedness (Part 1)

To address our first and second research questions concerning the roles of part-of-speech distinctions and action-relatedness in morphological derivation performance, we employed a 2X2 factorial design intersecting grammatical class (verbs vs. deverbal nouns) and action-related content (high vs. low). We were interested in comparing verbs with high action-relatedness (e.g., *sollevare* “to lift”) and deverbal nominals with high action-relatedness derived from those verbs (e.g., *sollevamento* “lifting”) with the

Italian suffixes *-mento*, *-zione, -tura*. Verbs with low action-relatedness (e.g., *leggere* "to read") and deverbal nominals with low action-relatedness (e.g., *lettura* "reading") served as control items.

In Part 1 of our modified task, participants were presented with a sentence containing a noun followed by a sentence with a gapped verbal position (N-to-V condition), or with a sentence containing a verb followed by a sentence with a gapped nominal position (V-to-N condition). Examples of elicitation sentences and corresponding target answers are provided in Table 14 (see also Appendix 2). Sentences used to elicit deverbal nouns were constructed to elicit the "event" reading of the deverbal (and not its "result" interpretation).

Table 14. Examples of Elicitation Sentences and Target Responses (Part 1)

Elicitation Sentence	Target Answer	Part of Speech	Action-Relatedness
*Il **sollevamento** del peso ha richiesto molta forza.* *Roberta ha fatto molta fatica per poterlo…* "**Lifting** the weight required a lot of strength. Roberta put in a great deal of effort in order to …. it"	sollevare "lift"	verb	high
*Andrea vuole **sollevare** il divano da terra.* *Andrea vuole riuscire nel suo faticoso…* "Andrea wants to **lift** the sofa off the floor. Andrea wants to succeed in his strenuous…"	sollevamento "lifting"	deverbal noun	high
*La **lettura** del romanzo ha richiesto tre mesi.* *A Nicola è servito molto tempo per poterlo…* "**Reading** the novel took three months. Nicola needed a lot of time in order to… it"	leggere "read"	verb	low
*Tamara vuole **leggere** le istruzioni della lavatrice.* *Tamara vuole dedicarsi alla loro…* "Tamara wants to **read** the washing machine instructions. Tamara wants to devote herself to their…"	lettura "reading"	deverbal noun	low

Our predictions were that, if one of the two parts of speech (verbs or deverbal nominals) was selectively impaired, this would provide evidence for a dissociation phenomenon in PD, although we did not expect this result. If both high action-relatedness verbs and the derived high action-relatedness deverbal nominals were impaired in PD, this would favour an interpretation of the deficit as connected to action-related conceptual content, endorsing the conceptual-semantic locus hypothesis (with low action-relatedness verbs and deverbal nominals expected to be spared). By contrast, if high action-relatedness items were impaired in PD only when they were encased into a CEN template, the deficit would be located at the interface with morphosyntax, thus advocating for a linguistically mediated locus of impairment.

7.2.1.2 Morphological Complexity (Part 2)

To address our third research question on whether and how morphological complexity of deverbal nominals modulates naming performance in PD beyond conceptual content, we compared simple nouns (e.g., *festa* "party") and zero-derived nouns (e.g., *scoppio* "burst") denoting events with morphologically complex synonyms bearing similar semantics (e.g., *celebrazione* "celebration", *esplosione* "explosion") of the "CEN" type (i.e., derived by suffixation with the eventive suffixes -*mento*, -*zione*, -*tura*). The latter type of stimuli is typically less frequent (*celebrazione* has an absolute frequency of 216,752 on *itTenTen20*, while *festa* has 1,443,421 occurrences), but the presence of the prime in the elicitation sentence helps limit frequency effects. Residual frequency differences were statistically controlled in the analysis.

The task was the same modified version of the NVR-SC task (Crepaldi et al., 2006). To elicit simple nouns, we used a coradical verb derived from the noun itself as a prime (e.g., *festa* "party", *festeggiare* "to party"). To elicit complex event nominals, we used the verb from which the noun itself derives (e.g., *combattimento* "fighting", *combattere* "to fight"). In Part 2, elicitation sentences with verbal primes were thus used to compare performance on the derivation of morphologically complex nouns and morphologically simple or zero-derived nouns while keeping their semantics as comparable as possible. This design allowed us to isolate the effect of morphological complexity on retrieval and derivation performance. Examples of elicitation sentences and corresponding target answers for this part of the task are provided in Table 15 (see also Appendix 2).

Table 15. Examples of Elicitation Sentences and Target Responses (Part 2)

Elicitation Sentence	Target Answer	Morphological Complexity
Lo scrittore vuole **complicare** *la trama del romanzo.* *Lo scrittore intende inserire un'ulteriore….* "The writer wants to **complicate** the plot of the novel. The writer intends to introduce an additional…"	complicazione "complication"	Complex Event Nominal (CEN)
Franco tende a ***problematizzare*** *ogni situazione.* *Franco è alla costante ricerca di un…* "Franco tends to make every situation **problematic**. Franco is in constant search of a…"	problema "problem"	morphologically simple noun

Our predictions were that, if morphologically complex deverbal nominals (e.g. *celebrazione* "celebration") and synonymous simple nouns denoting events (*festa* "party") were both impaired in PD, this would support of a purely semantic interpretation of the deficit. Conversely, if simple nouns are not impaired in PD but synonymous morphologically complex deverbal nominals are, morphology would play a role in PD patients' lexical competence. In particular, if morphological processes were impaired, this would provide us with a possible explanation for the observation that access to certain conceptual traits becomes problematic only when these traits are implemented in specifically linguistic processes.

7.2.2 Procedure

All participants were tested individually in a quiet environment. In both Parts 1 and 2, they heard and read a sentence containing a prime, followed by a sentence ending with a gapped final position. Stimuli were randomised such that each subject was presented with every prime-target pairing, but related pairs never appeared in consecutive trials. To counteract priming effects between items, elicitation sentences were divided into two lists, each of which presenting the related items of the task (e.g., *spostare* "move" and *spostamento* "movement") in the opposite order.

Participants were instructed to complete the second sentence by "saying aloud the missing word that was built from the word shown in bold" (the prime). Four training items were administered before proceeding with the experimental naming trials to familiarise participants with the task and ensure that they understood the instructions. They were asked to begin speaking only once the auditory presentation of the sentence had finished. All elicitation sentences were matched for overall length and syntactic structure. Sentences were displayed on the screen and accompanied by the corresponding recorded audio track presented via *E-Prime* software (version 3.0; Psychology Software Tools) and an external speaker. Participants were given unlimited time to provide their response and then pressed the spacebar to proceed to the next trial. Both accuracy and reaction times (speech onset) of verbal responses were collected.

As for accuracy, responses were coded binarily: any answer that was not coradical with the prime was scored as incorrect. When the participant provided more than one response, the first one was considered. Reaction times (RTs) were computed only for correct responses using a custom Python processing pipeline implemented with NumPy, SciPy, and SoundFile. The pipeline automatically extracted, for each trial, the temporal interval between the offset of the prerecorded elicitation sentence and the acoustic onset of the participant's vocal response. This was achieved by reading the waveform, detecting the end of the stimulus signal, and applying an amplitude-based detection to the participant's audio stream.

7.3 Statistical Analysis

All analyses were carried out in R (version 4.4.2). Accuracy and reaction times (RTs) data were analysed separately for the two parts of the elicited production task, corresponding to the different research questions addressed in Study 2.

7.3.1 Accuracy Analysis

Accuracy was treated as a binary outcome variable (correct = 1; incorrect = 0). To examine accuracy in the elicited production task, we first computed general descriptive statistics for each condition prior to modelling.

For Part 1, accuracy was examined by means of a mixed-effects logistic regression model (package *lme4*), which incorporated group (PD vs. HCM), part of speech (verb vs. deverbal nominal), and action-relatedness (high vs. low) as fixed predictors, together with log-transformed word frequency and word length, both z-scored, entered as covariates to control for low-level factors. Random intercepts were specified for both participants and items. Interaction terms (three-way interaction between group, part of speech, and action-relatedness) were evaluated through likelihood ratio tests and AIC differences ($\Delta AIC \geq 2$ adopted as meaningful improvement in model fit). When significant effects emerged, post hoc comparisons were carried out using estimated marginal means with Bonferroni-adjusted *p* values.

For Part 2, the analysis paralleled the structure described above, but accuracy was modelled as a function of group and morphological complexity, distinguishing CENs from their morphologically simple or zero-derived counterparts. Model comparison and post hoc procedures were conducted in the same manner as in Part 1.

7.3.2 Reaction Time Analysis

For the analysis of reaction times, only correct trials were considered. Reaction times were log-transformed to reduce skewness and analysed by fitting a series linear mixed-effects model (package *lmerTest*).

In Part 1, log-RTs were predicted by group, part of speech, and action-relatedness as fixed effects, with frequency and word length included as covariates. Interaction terms were entered sequentially and retained only when they significantly improved model fit in likelihood ratio tests. Random intercepts for participant and items were included. Pairwise post hoc comparisons were carried out using estimated marginal means with Bonferroni correction.

The analysis for Part 2 mirrored that of Part 1, substituting part of speech and action-relatedness with morphological complexity. Interaction effects involving group and morphological complexity were again assessed through model comparison procedures.

7.4 Results: Elicited Production Performance

7.4.1 Accuracy in Elicited Production

Overall accuracy across both tasks was quite high in both groups, with HCM participants outperforming PD participants by producing 95.5% correct responses on average (*SE* = 0.0056) compared with 70.8% (*SE* = 0.0482). Variability was low in the HCM group (*SD* = 0.033) but substantially higher in the PD group (*SD* = 0.268), indicating greater heterogeneity in performance for PD participants. A mixed-effects logistic regression on overall accuracy revealed a significant main effect of Group, with PD participants showing significantly reduced accuracy relative to HCM participants ($p < .001$). Log-transformed word frequency showed no detectable influence on accuracy ($p = .569$).

Accuracy by group and task revealed that HCM participants performed accurately in 97.1% (*SE* = 0.0039) of cases in Part 1 and 92.4% (*SE* = 0.0086) in Part 2. For PD participants, accuracy was lower overall, with 67.1% (*SE* = 0.0113) correct responses in Part 1 and 78.3% (*SE* = 0.0140) in Part 2. To examine whether accuracy differed across tasks and whether group effects varied by task, we fitted a mixed-effects logistic regression including Group (PD vs. HCM), Part (Part 1 vs. Part 2), and their interaction, with log-transformed word frequency as a covariate and random intercepts for participant and item. Inspection of item-level random effects revealed that three items (“aprire”, “divertire”, “scena”) had extreme ceiling or floor performance. These items were excluded in a follow-up robustness analysis. Importantly, the fixed effects and the Group x Part interaction remained unchanged after their removal.

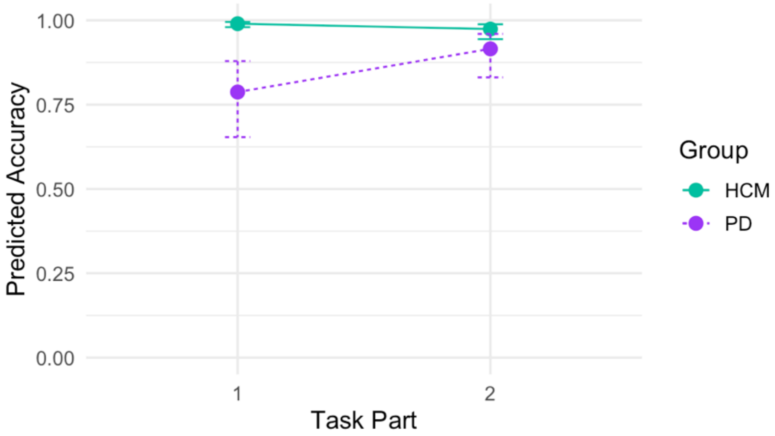


Figure 19. Predicted Accuracy for HCM and PD Across the Two Parts

The final model after outlier items removal revealed significant main effects of Group ($p < .001$) and Part ($p = .041$), qualified by a strong Group x Part interaction ($p < .001$; Figure 19). Pairwise comparisons confirmed that HCM participants were significantly more accurate than PD in both Part 1 ($p <.0001$) and Part 2 ($p = 0.007$). Within-group contrasts further showed that and that HCM were more accurate in Part 1 compared to Part 2 (p = 0.041), whereas PD participants were significantly more accurate in Part 2 compared to Part 1 (p < .0001). Log-transformed word frequency showed no significant effect on accuracy (p = .764). Random intercepts indicated variability across both items (*SD* = 1.078) and participants (*SD* = 1.672), indexing considerable heterogeneity in response patterns.

Analyses were then conducted separately for the two tasks. In Part 1, the manipulated factors were part of speech (deverbal nominal vs. verb) and action-relatedness (high vs. low). All deverbal nominals in this task were complex event nominals with an eventive reading, and half of the low action-relatedness items referred to psychological processes.

Accuracy patterns for Part 1 showed uniformly high performance in the HCM group across all conditions. HCM participants achieved between 95.6% and 97.7% accuracy across all combinations of part of speech and action-relatedness level. In contrast, PD participants showed lower accuracy overall, ranging from 64.5% to 69.6% for deverbal nominals and from 66.1% to 68.0% for verbs. Despite remaining below HCM performance, accuracy in the PD group slightly increased for items with higher action-relatedness (Table 16, Figure 20).

Table 16. Accuracy in Part 1 by Group, Part of Speech, and Action-Relatedness

Group	Part of Speech	Action-Relatedness	n	Mean Accuracy	SE
HCM	deverbal noun	low	476	0.98	0.01
HCM	deverbal noun	high	475	0.96	0.01
HCM	verb	low	476	0.97	0.01
HCM	verb	high	475	0.97	0.01
PD	deverbal noun	low	434	0.65	0.02
PD	deverbal noun	high	434	0.70	0.02
PD	verb	low	434	0.66	0.02
PD	verb	high	434	0.68	0.02

To assess whether the accuracy patterns observed in Part 1 were statistically reliable, we fitted a mixed-effects logistic regression including Group, Part of Speech (deverbal nominal vs. verb), Action-Relatedness (high vs. low), and all interactions, with log-transformed word frequency and word length as covariates. Random intercepts for both participant and item were included. Two items ("aprire" and "divertire") showed ceiling performance and were removed from the dataset. Refitting the model after item removal did not alter the pattern of results.

The final model revealed a significant main effect of Group, with PD participants performing less accurately than HCM participants (p < .001). Neither Part of Speech nor Action-Relatedness yielded significant main effects (both p > .17). Importantly, the analysis revealed significant interaction effects. A Group x Action-Relatedness interaction was present (p = .026), and critically, a three-way Group x Part of Speech x Action-Relatedness interaction also emerged as significant (p = .028). Model comparison supported the inclusion of both interaction terms, as removing the three-way interaction significantly worsened model fit (LRT: $\chi^2(1) = 4.87$, $p = .027$; ΔAIC = 2.87), and the Group x Action-Relatedness interaction also met the ΔAIC ≥ 2 criterion for improved fit (ΔAIC = 2.01). These results indicate that group differences in accuracy were modulated jointly by part of speech and action-relatedness, rather than reflecting a uniform deficit across conditions.

Post hoc comparisons examining group differences within each condition confirmed that HCM participants performed significantly more accurately than PD participants across all combinations of part of speech and action-relatedness (all $p < .0001$, Bonferroni-corrected). Although the overall pattern showed consistently reduced performance in the PD group, the magnitude of the group difference varied across conditions, in line with the significant three-way interaction. In particular, for deverbal nominals, the difference in accuracy between HCM and PD was significantly smaller for high-action items ($p = .348$) compared to low-action items ($p = .026$), indicating a benefit of action-relatedness for PD participants. In contrast, for verbs the groups did not differ across action-relatedness levels ($p = .35$).

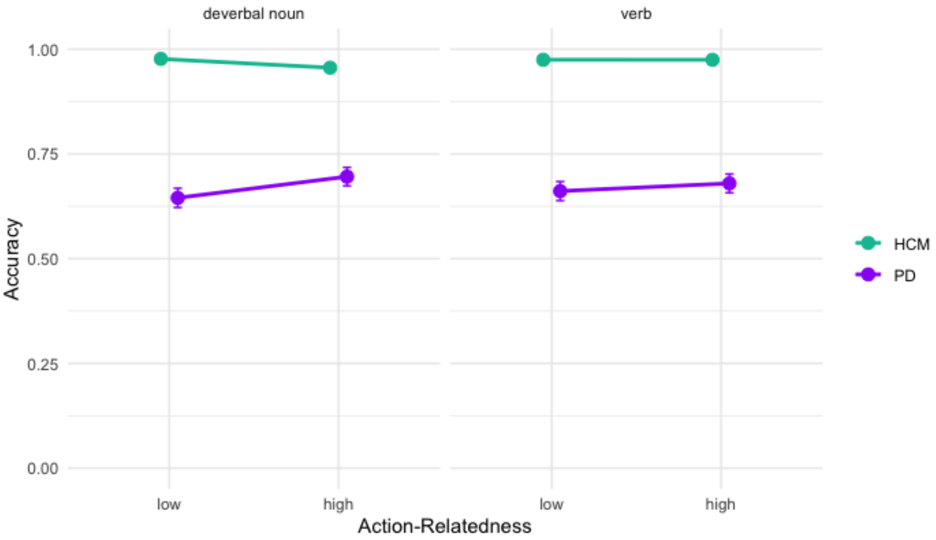


Figure 20. Part 1. Accuracy by Group, Part of Speech, and Action-Relatedness

An additional descriptive analysis was conducted to determine whether, among the low action-relatedness items, those encoding psychological processes exhibited different accuracy patterns from those that did not involve psychological processes. In the HCM group, accuracy remained uniformly high across all low-motion conditions, ranging between 96.6% and 98.9%, while in the PD group accuracy was considerably lower and identical for deverbal nouns (64.5%), irrespective of their psychological content. In the case of verbs, psychological content yielded a small improvement for PD participants, who produced 67.3% correct responses compared with 65.0% for non-psychological verbs. No effects involving psychological content reached statistical significance (all $p > .38$).

Part 2 manipulated morphological complexity by comparing complex event nominals (CENs) with their morphologically simple or zero derived counterparts. As in Part 1, HCM participants performed with high accuracy across all morphological types, producing between 90.8% and 94.0% correct responses. In the PD group, accuracy was lower overall but varied across categories: PD participants achieved 77.4% accuracy on simple forms, 79.7% on zero-derived forms, and 68.4% on CENs (Table 17, Figure 21), suggesting a disproportionate difficulty with morphologically complex items.

Table 17. Accuracy in Part 2 by Group and Morphological Complexity

Group	Morphological Complexity	n	Mean Accuracy	SE
HCM	simple	254	0.83	0.02
HCM	CEN	460	0.97	0.01
HCM	simple_zero	238	0.93	0.02
PD	simple	233	0.75	0.03
PD	CEN	418	0.81	0.02
PD	simple_zero	217	0.77	0.03

To assess whether these differences were statistically reliable, accuracy in Part 2 was modelled using a mixed-effects logistic regression including Group, Morphological Category (simple vs. zero-derived vs. CEN), and their interaction, with log-transformed word frequency and word length entered as covariates, and random intercepts for participant and item. The model revealed no significant main effect of Group ($p = .143$) and no significant overall main effect of Morphological Category ($p = .843$), indicating that neither factor alone reliably explained variation in accuracy. However, a robust Group x Category interaction emerged ($p = .002$), indicating that group differences varied as a function of morphological complexity, and driven by disproportionately reduced accuracy for CENs in the PD group. This interaction significantly improved model fit, as confirmed by both the likelihood-ratio test ($\chi^2(1) = 8.92$, $p = .003$) and the AIC decreased by 6.9 points ($\Delta AIC \geq 2$), and was therefore retained in the final model.

Post hoc comparisons based on estimated marginal means clarified the interaction pattern. For CENs, PD participants were substantially less accurate than HCM participants (log-odds difference = -2.25, odds ratio = 9.5, $p < .001$, Bonferroni-corrected). For zero-derived forms, a smaller but still significant group difference was observed (odds ratio = 4.2, $p = .004$), whereas no significant group differences emerged for morphologically simple forms ($p = .14$), where PD performance approached that of the HCM group. Taken together, these findings indicate that morphological complexity most strongly exacerbated accuracy deficits in PD participants on CENs, with a moderate impairment also present for zero-derived forms and preserved performance on simple nouns. In the HCM group, by contrast, accuracy remained uniformly high across all morphological types, consistent with the absence of a main effect of Category.

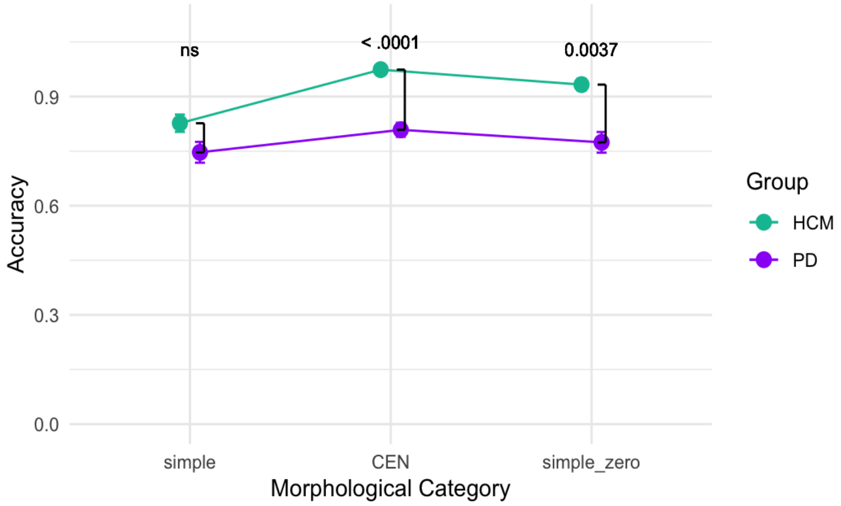


Figure 21. Part 2. Accuracy by Group and Morphological Complexity

7.4.2 Reaction Times of Elicited Production

Reaction times (RTs) were analysed on correct trials only. RTs were log-transformed to reduce skewness. A linear mixed-effect model including Group, Part of Speech, and Action-Relatedness as fixed effects, with log-transformed word frequency and word length entered as covariates, and random intercepts for participant and item, was fitted to log-RTs. Interaction terms were added sequentially and retained only when they significantly improved model fit. None of the higher-order interactions (all LRT $p > .22$) contributed to the model, and thus the final model included only main effects.

The final model revealed a robust main effect of Group, with PD participants producing significantly longer reactions times than HCM participants ($p < .001$). Neither Part of Speech nor Action-Relatedness yielded significant effects (both $p > .08$), indicating that RTs did not vary reliably between verbs and deverbal nouns or between high and low-action items. Log-transformed word frequency exerted a modest facilitation effect ($p = .023$), whereas word length showed no reliable influence on reaction times ($p = .138$). No interactions involving Group were detected, suggesting that the RT slowing observed in PD was consistent across all lexical conditions.

RTs for Part 2 were analysed on correct trials only, with RTs log-transformed prior to conducting the analysis. A linear mixed-effects model was fitted with Group and Morphological Category (CEN vs. simple vs. zero-derived) as fixed effects, along with log-transformed word frequency and word length as covariates. Random intercepts for participant and item were included. As for Part 1, interaction terms were added sequentially and retained only when they significantly improved model fit.

The Group x Category interaction did not significantly improve model fit (LRT $p = .718$), and the final model therefore included only main effects. A reliable main effect of Group emerged, with PD participants showing significantly longer reaction times than HCM ($p < .001$). In contrast, Morphological Category did not influence RTs. Neither frequency nor word length exerted significant effects on RTs. No interaction involving Group was observed in terms of reaction times.

7.5 Discussion

The present study investigated whether morphological derivation processes, and in particular deverbal nominalisation, reveal selective vulnerabilities in PD, above general conceptual deficits. Overall, the pattern emerging from the two parts of the task indicates that PD does not show a category-wide noun-verb dissociation, nor a general action-semantic deficit, but rather a more circumscribed impairment affecting the interface between the linguistic encoding of event structure and morphosyntactic encoding. Crucially, this pattern was most clearly reflected in accuracy, whereas reaction times showed only a global slowing. This is particularly noteworthy given that much of the previous literature has emphasised disadvantages for action-related material in PD. What we found here, instead, is that sensorimotor richness tends to have a facilitative role rather than a detrimental one.

7.5.1 Reaction Times: Slowing in PD without Selective Morpho-Syntactic Effects

Reaction-time analyses across both parts of the task revealed the expected main effect of Group: PD individuals were consistently slower than healthy controls. Beyond this global slowing, however, reaction times did not show selective effects of part of speech, action-relatedness, or morphological complexity, nor interactions between these factors and Group.

At first sight, this might seem at odds with the accuracy data, where clear selectivity emerged. However, this dissociation between accuracy and RTs is theoretically interpretable and methodologically expected given the task design. First, the elicited production paradigm strongly encourages predictive morphological processing. Upon hearing the prime in the first sentence, participants, especially healthy controls, can pre-compute the morphologically appropriate target well before the second sentence ends. As a result, the latency measured from the end of the sentence to speech onset may reflect mainly articulation planning rather than the core derivational process. Any difficulty in deriving *sollevamento* “lifting” from *sollevare* “to lift”, for instance, is likely to be resolved (or not) *before* the time window captured by the RT measure. Second, RT responses were conducted only on correct responses. The very trials where PD participants experienced the strongest derivational or interface-level difficulty often resulted in an incorrect response, and these were necessarily excluded from RT analyses. Thus, the subset of trials on which latencies are measured is biased towards those in which processing was relatively successful. This naturally attenuates any condition-specific RT differences. Third, when derivation fails, PD participants do not necessarily struggle longer before producing the correct word. Rather, they often quickly supply a contextually plausible substitute that is not morphologically coradical with the prime. In such cases, processing difficulty manifests as a shift in response type (accuracy-related) rather than an increase in reaction time. This pattern explains why accuracy and not RTs emerges as the more sensitive marker of selective morpho-syntactic and conceptual vulnerabilities in the present study.

7.5.2 Accuracy: Selective Vulnerabilities rather than Global Deficits in PD

In contrast to the RT results, accuracy provided a much richer and more differentiated picture. As expected, PD participants were overall less accurate than healthy controls. However, this reduction in accuracy was not uniform across conditions, and its contribution is highly informative about PD-related impairment and its locus.

At the global task level, PD participants were significantly less accurate than HCM in both parts, but performed better in Part 2 than Part 1, whereas controls showed the opposite pattern. This already suggests that PD participants were more challenged when conceptual and morphosyntactic demands interacted simultaneously, a point developed below. Importantly, within each of the two task parts, accuracy patterns were modulated by linguistic structure and conceptual content in a way that cannot be reduced to a simple noun-verb dissociation or a general action-semantic deficit. In line with this, Study 2 adds to the picture emerging from Chapter 6 that PD difficulties do not stem from a primary deficit in conceptual representations, but from how these representations are manipulated and reconverted into the linguistic system.

7.5.2.1 Morphological Complexity and Complex Event Nominals

Part 2 directly tested whether morphological complexity itself modulates performance in PD by keeping semantics as constant as possible and comparing simple event nouns, zero-derived event nouns, and morphologically complex CENs derived by suffixation (*-mento*, *-zione*, *-tura*). In this case, healthy controls again performed at high accuracy across all morphological conditions, with no strong sensitivity to morphological complexity. PD participants, however, showed a graded pattern: simple nouns showed preserved accuracy, zero-derived nouns mildly reduced accuracy, and CENs a selective drop in accuracy. This graded pattern leads to the identification of several important theoretical implications. First, it argues against a purely semantic explanation of the deficit. If PD individuals were simply impaired in building or accessing the relevant event semantics, then both the morphologically complex CENs and their simple or zero-derived synonyms should have been similarly affected. The fact that simple event nouns were spared while CENs were impaired indicates that linguistic semantics alone cannot account for the pattern.

Second, the pattern of results points to the role of morphological and structural complexity. In particular, the difficulty increases proportionally to the degree of morphological computation required. This aligns with rule-based accounts of derivational morphology (e.g., Ullman, 2016). Simple nouns, which are retrieved from lexical memory and require a minimal computation, are spared in PD. Zero-derived nouns, which require access to a zero morpheme (a light derivational operation), display a mild difficulty. CENs, which are widely assumed to inherit verbal eventive structure and A-structure, and thereby to involve additional functional projections in their syntactic representation, require a complex derivational operation and display the highest difficulty in PD. This pattern is fully compatible with known fronto-striatal and basal ganglia involvement in rule-based morphological computation. Patients with PD, whose fronto-striatal circuitry is compromised, are predicted to struggle especially with rule-demanding derivations, while relying more heavily on stored forms. Our data align closely with this prediction.

Third, Part 2 also provides evidence that derivational morphology *per se* is not enough to induce impairment. All conditions involved a derivational step, as the task always required building a form from a prime, yet the deficits were not uniform. Instead, PD performance worsened in the derivational operation in a selective fashion, namely when structural integration of conceptual event features and argumental structure of the verbal root inside a nominal template was required (CENs). The impairment does not reflect a global difficulty with morphological derivation, but rather the linguistic operations that bind event structure into morphosyntactic frames. In other words, even when derivation is required across the board, performance follows a graded storage-computation hierarchy, with forms that can be largely retrieved from lexical memory (e.g, *guerra* "war") are easier than forms that require full-fledged derivational computation (e.g., *combattimento* "fighting").

Finally, the graded difficulty (simple → zero → CEN) reflects a different degree of morphological productivity (cf. Yang, 2016). CEN-deriving suffixes (*-mento*, *-zione*, *-tura*) represent highly productive, rule-based morphological processes, simple nouns depend almost entirely on storage, and zero-derivation occupies an intermediate zone. The pattern in PD mirrors this hierarchy: the more computation a derivation requires, the greater the impairment. This makes the balance between storage and computation a central dimension for interpreting PD performance in derivational tasks, and suggests that the core vulnerability lies in processing morphosyntactic representations and connecting them to the stored event-structure representations, rather than simply in building or accessing these event-structure representations.

7.5.2.2 Part of Speech and Action-Relatedness: Conceptual-Morphosyntactic Interface

In Part 1, we jointly manipulated part of speech (verb vs. deverbal nominal) and action-relatedness (high vs. low). If PD were characterised by a simple grammatical dissociation (e.g., a deficit for verbs), we should have observed lower accuracy for verbs than for deverbal nominals (or vice versa) across the board. If PD were instead characterised by a general action-semantic deficit, we should have observed impairments for high action-relatedness items irrespectively of their category. Neither of these two predictions was upheld by the data.

Instead, accuracy in PD showed a three-way interaction between Group, Part of Speech, and Action-Relatedness. Healthy controls performed near ceiling in all conditions, whereas PD participants showed reduced accuracy with specific modulations. For verbs, accuracy in PD did not differ substantially between high and low action-relatedness. For deverbal nominals, by contrast, high action-relatedness provided some benefit, with smaller group differences for high-action CENs than for low-action ones. This pattern indicates that action-relatedness did not turn out to be a source of deficit in PD and on the contrary it was beneficial under certain morphosyntactic configurations. This is striking when contrasted with previous findings in PD, where high motion or strong sensorimotor content often yielded worse performance. Here, by contrast, the same features tend to facilitate processing in at least some conditions.

Crucially, the conceptual property of action-relatedness becomes behaviourally relevant in PD only when embedded in the linguistic template of deverbal nominals (e.g., *compressione* "compression"), and not when expressed as a verb (e.g., *comprimere* "to compress"). This resonates closely with the findings of Chapter 6, where impairments emerged specifically when conceptual features such as causation and mental involvement had to be expressed through particular lexical-syntactic templates (e.g., internally agentive verbs, nouns denoting artefacts with implicit action structure), rather than at the level of the conceptual system *per se*. One possible interpretation is that PD participants can access, and sometimes even over-recruit, action-related features at the conceptual level, which leads to facilitation in certain linguistic configurations. In other words, Part 1 suggests that PD does not disrupt either lexical category (noun vs. verb) or action semantics as such. Instead, difficulties emerge most clearly when eventive, argument-structure-bearing morphosyntactic templates such as CENs are not supported by strong action-relatedness cues, as in low action-relatedness deverbal nominals. By contrast, high action-relatedness within the same CEN structure can partially compensate this vulnerability.

The accuracy results from Part 2 provide a morphological mirror of the findings of Study 1 (Chapter 6). There, the PD group was disproportionally affected by items that encoded causation and agentivity through specific morphosyntactic configuration. Here, PD is disproportionately affected by nominal forms that encode event structure through suffixation, again implicating the conceptual-morphosyntactic interface rather than semantics or lexical category alone. The accuracy results from both Tasks 1 and 2 converge on a coherent interpretation: PD selectively struggles with morphologically complex forms that encode verbal eventive structure within the nominal system, suggesting that the relevant impairment concerns the connectivity between different level of linguistic computation rather than building or accessing a single level of conceptual/linguistic representation.

7.5.2.3 Task Demands and Heterogeneity in PD

Within-group variability in the PD group was very high, and any interpretation of the results must be situated within this context. The tasks employed in this paradigm are demanding not only linguistically but also cognitively, since they require participants to maintain the prime word and the constraining instruction ("build the missing word from the prime in bold") over the course of a relatively long sentence, and select a target that is not only contextually appropriate but also morphologically coradical with the prime. A frequent behaviour observed in the PD group was the re-reading of part or all of the elicitation sentence before producing the response, suggesting that some participants were relying on external support to compensate for reduced maintenance. This is in line with working memory and executive vulnerabilities in PD. Although sentence length and structure were carefully controlled across items, the richness of the contextual information may have increased semantic interference: the sentence context activated several plausible candidates, but only one was derivationally licit. PD participants might have experienced difficulties in selection under competition and have been particularly susceptible to context-driven but non-coradical responses.

These task-related considerations help explain the overall reduction in accuracy and the variability within the PD group, but they do not undermine the specificity of the main findings. Since working memory load and contextual richness were kept constant across conditions, general task demands cannot account for the selective disadvantage for CENs in Part 2 and the specific interaction between part of speech, action-relatedness and group found in Part 1. On the contrary, the working memory and interference demands should be considered as an amplifier of individual vulnerability, on the basis of which the more fine-grained structural effects become evident.

7.6 Summary and Conclusions

Study 2 provides novel evidence that derivational morphological processes in PD are modulated by both conceptual (action-relatedness) and linguistic (morphosyntactic) factors. This paradigm leverages the hybrid status of deverbal nominals: because they embed verbal event structure within a nominal frame, they are particularly revealing for probing phenomena occurring at the conceptual-morphosyntactic interface. The present findings indicate that PD is especially challenged when the integration between conceptual and morphosyntactic features is required, potentially due to disruption of fronto-striatal circuit that might support such linguistic operations in healthy individuals. Overall, the two parts of Study 2 offer converging evidence that morphological competence in PD is not uniformly impaired, but is selectively modulated by the interface between conceptual-semantic content and the morphosyntactic scaffolding through which that content has to be linguistically expressed. Contrary to our expectations, reaction times did not show significant selective deficits in the PD group. This likely reflects characteristics of the task design: RTs were measured on correct trials only and starting from the offset of the elicitation sentence, while the core derivational processes are often resolved earlier in the trial. Crucially, deficits were more likely to emerge in terms of accuracy. In particular, as demonstrated by Part 1, action-relatedness did not result in a generalised impairment in PD individuals. Rather, this conceptual feature exerted a facilitation effect only when it was realised within the linguistic template of deverbal nominals, and not in the corresponding verbal forms. Low action-relatedness deverbal nominals, by contrast, turned out to be selective vulnerable in PD. Along this line of interpretation, Part 2 provided converging evidence in terms of morphological complexity. When morphological complexity was higher, as in complex event nominals (where suffixation applies), PD participants were selectively less accurate than controls. This pattern was not present when recalling morphologically simple nouns, where the two groups did not differ. The fact that the PD group selectively struggles with CENs provides psycholinguistic support for the view that these forms are not merely semantically richer, but also structurally more demanding than their simple counterparts. Crucially, even in Study 2 there is no indication of a direct impairment for action-related concepts themselves. What emerges is instead a vulnerability of the computations that embed these concepts into morphologically complex, rule-based linguistic formats.

Taken together, these findings align with those from Chapter 6 in suggesting that lexical access difficulties in PD do not arise from a global impairment in processing action semantics, but from a selective vulnerability of linguistically mediated representations of conceptual traits. By focusing on morphology, Chapter 7 provides additional evidence for the fact that PD affects the integration of conceptual and linguistic information during lexical retrieval, with particular difficulty when conceptual event structure must be encoded within morphologically complex nominal templates. From this perspective, the central question does not concern whether concepts are available, but how they are stored versus computed, and the present results suggest relatively preserved storage of conceptual content and increased fragility of the morphosyntactic computations required to derive morphologically complex nominal forms.

Chapter 8 – Eye-Tracking-Based Implicit Learning in Parkinson's Disease (Study 3)

This chapter builds upon the theoretical background outlined in Chapter 3, entitled "Implicit Learning in Parkinson's Disease", and presents a novel experimental study that aims at assessing implicit learning abilities in this population. Implicit learning, or "implicit statistical learning", as it was termed in recent literature (Christiansen, 2019) in an attempt to reconcile two streams of research dealing with the same construct, refers to the incidental acquisition of knowledge through the extraction of regularities from sensory input. This domain-general mechanism is believed to underpin higher-level cognitive functions such as language, memory, and attention. Previous literature on implicit learning in PD has yielded mixed results (Hayes et al., 2015; Witt et al., 2006), sometimes supporting and sometimes contradicting the presence of an actual deficit. These inconsistencies may stem from methodological differences and from the influence of dopaminergic therapy, which can also affect implicit learning performance.

A crucial task-related factor that exerts an effect on participants' performance is motor involvement. Because many tasks commonly used to investigate this construct require overt motor responses, it remains uncertain whether the observed deficits in PD reflect impaired learning or rather motor dysfunction. In general, when motor demands are low, individuals with PD tend to perform relatively well on implicit learning tasks, suggesting a preserved sensitivity to the regularities underlying the stimuli.

Another important task-related dimension concerns prediction demands. As observed in Chapter 3, protocols that operationalise implicit learning through probabilistic classification tasks consistently show vulnerability in PD (Sage et al., 2003). This pattern is commonly attributed to degeneration within the striatum, a structure central to the incremental, feedback-driven learning required by these tasks. More recent evidence additionally suggests that performance also depends on the broader basal ganglia-frontal circuitry. For example, stimulation of the subthalamic nucleus (STN) selectively improves learning of weakly associated cue-outcome pairs in PD, indicating that the STN contributes to the implicit components of probabilistic classification learning by modulating basal ganglia output to the frontal cortex (Wilkinson et al., 2011).

The heterogeneous evidence coming from implicit learning studies in PD highlights the need for precise terminology and detailed methodological reporting, especially regarding task requirements and participants' treatment and clinical state, to enable meaningful interpretation of implicit learning skills in this population. In this context, our study sought to develop an implicit statistical learning protocol capable of effectively distinguishing individuals with PD from neurotypical matched controls. The ultimate goal was to assess the potential diagnostic value of implicit learning measures as biomarkers, contributing to a broader, non-motor-based understanding of PD and potentially supporting earlier diagnosis.

To avoid conflating motor and cognitive components of performance, we designed a task that combined traditional button-press responses with eye-tracking, allowing for the online recording of predictive gaze behaviour. Eye-tracking offers an opportunity to detect implicit learning effects beyond potential motor (button-press) differences, as it captures anticipatory eye movements that reflect automatic, pre-conscious processing. Moreover, to vary the learning demands placed on the basal ganglia-frontal circuits, we tested the acquisition of different types of regularities, encompassing both deterministic transitional regularities and less predictable, probabilistic ones. This dual manipulation allowed us to examine the contribution of both motor and striatal functioning to implicit statistical learning in PD. Figure 22 illustrates the experimental design and how the task manipulates motor demands from low (eye-tracking-based) to high (button-press-based), depicted along the horizontal axis, and the striatal demands of the learned regularities from low (deterministic) to high (probabilistic), depicted along the vertical axis.

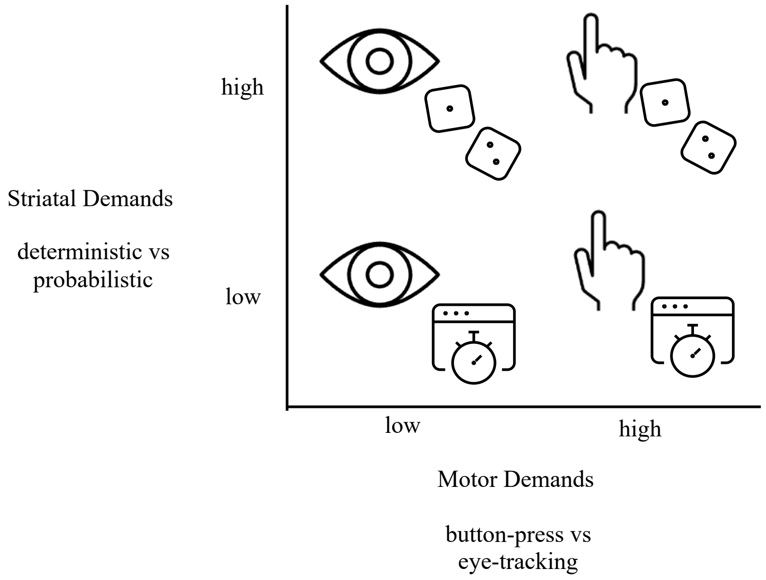


Figure 22. Experimental Design Matrix of Striatal and Motor Demands

Building on these considerations, Chapter 8 (Study 3) therefore addresses the following research questions:

(1) Do individuals with PD and control participants implicitly acquire the transitional regularities underlying a sequence of visually presented stimuli?
(2) Do their motor responses throughout the task reflect learning?
(3) Do they perform anticipatory eye movements towards the target visual area, thereby demonstrating learning through predictions of the upcoming stimuli?

In our design, behavioural performance in the SRT task serves as an indirect measure of implicit learning of the presented sequence. However, because the motor demands required for button-press responses may place a disproportionate burden on individuals with PD, learning-related effects can be obscured in the PD group. To overcome such confound, we complemented the SRT task with an eye-tracking paradigm that assesses learning through online anticipatory oculomotor behaviour. Anticipatory fixations require only minimal motor output, thereby reducing the interpretative ambiguity that arises when impaired motor execution and impaired learning are difficult to disentangle.

Furthermore, this combined approach enables us to examine sensitivity to regularities that vary in complexity. If individuals with PD exhibit intact anticipatory oculomotor behaviour, this would align with evidence suggesting preserved implicit learning and sensitivity to structure under low motor demands. Conversely, reduced sensitivity to the regularities in the prediction part of the task would support the view that striatal dysfunction undermines reinforcement-based implicit learning. Finally, if PD performance is preserved across all conditions, both motor-based and eye-tracking-based, this would point toward the recruitment of compensatory mechanisms outside the striatum.

8.1 L-Systems, the Fibonacci Grammar, the Alternation Bias and the Rotating Players

A grammar *G* is a set of rules applying over a finite alphabet to generate strings. The tool offered by artificial grammars is a methodologically powerful one, because it allows researchers to investigate the acquisition of structural regularities, such as those underlying language processing, under highly controlled conditions. In particular, artificial grammars make it possible to assess implicit learning of regularities in conditions that are entirely free of semantic content, thereby isolating pattern-learning mechanisms from language-based influences. Our paradigm featuring an artificial grammar therefore offers an a-linguistic perspective, useful for cross-linguistic comparisons and for investigating both typical and atypical populations, including children and individuals with linguistic or non-linguistic impairments (Christiansen et al., 2010; Don et al., 2003; Reber et al., 2003).

A particularly intriguing type of artificial grammar is represented by Lindenmayer systems (L-Systems), originally developed to model plant growth and bacterial reproduction (Lindenmayer, 1968). When comparing these grammars to those belonging to Chomsky hierarchy (Chomsky, 1959), a number of peculiarities emerge.

In the grammars of the latter type, rewriting rules apply over an alphabet that distinguishes between nonterminals (symbols that can be rewritten) and terminals (symbols that cannot be rewritten and constitute the final strings).

L-systems, in contrast, are defined as recurrence relations: given an initial state, each subsequent state of the system can be defined as a function of the preceding ones (see also Krivochen & Saddy, 2018). Like other formal grammars, L-systems have a finite alphabet, a set of states, and transition functions between states. However, some properties are hallmarks of L-systems only. Most notably, L-symbols simultaneously hold both statuses of terminals and nonterminals, as they both make up a string and rewrite to compose the next generation. As a result, unlike the grammars in the Chomsky hierarchy, L-grammars lack a labelling procedure, since any element can be rewritten. A second major difference pertains to the hierarchy of rewriting rules. While grammars belonging to the Chomskyan hierarchy apply rules sequentially following the so-called "traffic convention", L-systems are characterised by a simultaneous application of rewriting rules in a top-down fashion, reflecting their biological inspiration as models of growth and multiplication in biological species (see Krivochen & Saddy, 2018 for a comprehensive classification of L-systems and their properties). Moreover, L-grammars exhibit self-similarity, entailing that any pattern found in a given derivation maps onto earlier generations (see Vender et al., 2020; Krivochen, 2025). These features make L-systems especially suited for studying implicit learning mechanisms that rely on hierarchical recursive structure.

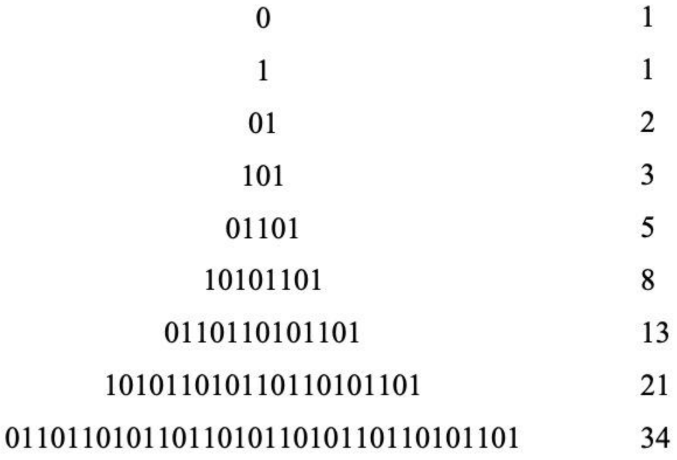
A number of studies have directly examined implicit learning of Fibonacci-generated sequences and provide relevant evidence for our purposes. In a first study using a modified Simon task, Vender et al. (2019) showed that both bilingual and dyslexic participants were sensitive to the deterministic transitions of the Fibonacci grammar. Despite overall group differences, all populations successfully learned that specific items were fully predictable and exhibited faster reaction times at those deterministic points. A subsequent study (Vender et al., 2020) reported not only robust learning of deterministic transitions but also above-chance performance at non-deterministic points, where no item is strictly predictable based on the transition probabilities of the linear sequence of stimuli. This counterintuitive result suggests that participants did not rely solely on surface-level transitional statistics but instead engaged in some form of structural analysis. Two lines of interpretation have been proposed. One view, developed in Vender et al. (2023), posits a limited but genuine structural reconstruction: participants may treat linear precedence relations as projections in a bidimensional space, allowing them to detect higher-order regularities that support partial predictions even in non-deterministic contexts. A complementary hypothesis supported by Schmid (2023) is that learners build increasingly long chunks of Fibonacci strings. Once these larger chunks are internalised, transitions that are non-deterministic at the atomic level become effectively predictable at the chunk level. Across these accounts, a shared theoretical conclusion emerges: humans tend to compute over symbol sequences by reconstructing hierarchical structure, what has been termed *dendrophilia*, rather than relying solely on shallow linear statistics. This body of evidence therefore demonstrates that implicit learning of L-system-based grammars can occur at multiple representational levels, capturing both deterministic and non-deterministic regularities.

When using binary stimuli and responses, as in the present study with blue [0] and red [1] stimuli, it is essential to control for the so-called "alternation bias", a phenomenon related to the "gambler's fallacy", namely the mistaken belief that the likelihood of an event is influenced by previous outcomes, even when events are statistically independent. This phenomenon has attracted interdisciplinary interest, from economics to neuroscience. In binary-choice tasks, participants typically respond faster to alternating stimuli (e.g., ABAB) than to repeated ones (e.g., AABB), and this pattern is referred to as the "alternation advantage" (Fecteau et al., 2004; Soetens, 1998; Kirby, 1976). This effect has been documented not only in manual but also in oculomotor responses (Bertelson, 1961; Fecteau et al., 2004; Gao et al., 2009; Williams, 1966). The cognitive nature of this bias remains debated: it is not clear whether it reflects alternation in the perceived stimulus locations or in the motor/oculomotor responses themselves. This debate parallels the broader question of what is learned in implicit statistical learning. Some researchers propose a perceptual view, whereby participants learn associations between stimuli; others favour a motor account, emphasising the sequence of responses. A third view integrates both, suggesting that participants acquire associations between stimuli and responses. A recent study further examined how the alternation advantage interacts with implicit learning of Fibonacci-generated sequences, showing that the bias emerged in both manual and oculomotor responses and interacted with the regularities of the sequence, thereby influencing the observable implicit learning effects (Compostella et al., 2025).

8.1.1 Implicit Learning Protocol

In this study, we designed a modified Serial Reaction Time (SRT) task featuring visual stimuli arranged according to the rules of the Fibonacci grammar. Participants' button-press responses provided measures of accuracy and reaction times, while eye-tracking captured predictive gaze patterns towards target areas of interest (AOIs) corresponding to the upcoming stimuli. These anticipatory eye movements were used as an index of implicit, online processing of statistical regularities.

The Fibonacci grammar operates on a lexicon composed of two symbols, [0] and [1], and two rewriting rules: [0] → [1] and [1] → [01]. Applying these rules recursively yields successive generations in which each string has a number of symbols that progresses according to the Fibonacci sequence, hence the grammar's name (Figure 23).



0	1
1	1
01	2
101	3
01101	5
10101101	8
0110110101101	13
101011010110110101101	21
0110110101101101011010110110101101	34

Figure 23. Fibonacci Tree Resulting from a Fibonacci Grammar Derivation

Note. The tree-like structures of [0] and [1] illustrate successive Fibonacci generations. The numbers in the right column show the total count of symbols in each generation, forming the sequence that gives the grammar its name.

Across these strings, several transitional regularities hold:

1) First regularity: [0] is always followed by [1] (so the string *[00] would be ungrammatical);
2) Second regularity: [11] is always followed by [0] (so *[111] would be ungrammatical);
3) Third regularity: [01] can be followed by either [0] or [1], meaning that both [010] and [011] are possible trigrams. The point [01] thus represents a locally ambiguous point, as the following symbol is probabilistic rather than deterministic, unlike the previous two rules.

To disentangle these types of regularities, we implemented a modified SRT task using stimuli generated by the Fibonacci artificial grammar, presenting both deterministic ([01], [110]) and probabilistic ([011], [010]) points. Participants responded to each visual stimulus by pressing the corresponding coloured button on a response box (red or blue), yielding measures of accuracy and reaction times throughout the task that reflect a motor-based component of learning. Crucially, eye-tracking was employed as an online measure to identify predictive eye movements toward the relevant AOI, indexing a more automatic, pre-conscious response to stimulus regularities.

The advantage of integrating eye-tracking lies in its ability to capture implicit anticipatory behaviour beyond overt motor performance. Whereas behavioural measures depend on deliberate responses, eye-tracking taps into low-level, automatic reactions that may reveal sensitivity to structural regularities even before an explicit response is made. Humans are constant prediction-makers, anticipating upcoming events before they unfold. Eye-tracking leverages this natural tendency: people often fixate the target before it appears, and occasional prediction errors, when expectations are violated, can be used to infer how implicit knowledge evolves during learning. This approach offers a window into participants' sensitivity to the rules underlying the stimuli, providing a dynamic and continuous measure of implicit statistical learning.

To address the issue related to the alternation advantage reported in the literature and to ensure that our data reflected genuine implicit learning rather than orthogonal cognitive biases, we developed a rotating design featuring four possible stimulus positions. In this paradigm, two players rotated 90° anticlockwise after each trial, allowing each stimulus (blue [0] or red [1]) to appear in four distinct locations (Figure 24). This setup functioned as a strict two-choice task from the motor perspective, requiring a binary button-press response, and as a four-choice task from the visuo-perceptual point of view, therefore eliminating the binary perceptual component that typically contributes to the alternation bias.

A pilot study with 23 native Italian speakers (Age: $M = 26.2$ years; $SD = 3.18$ years) with normal or corrected-to-normal vision and no speech, hearing, or language disorder confirmed that the rotating design successfully tamed the alternation bias. Analyses revealed no statistically significant differences in reaction times between [010] (alternation) and [011] (repetition) sequences, and no accuracy differences in predictive oculomotor behaviour toward the target AOI. Even in later blocks, no trend suggested a delayed emergence of alternation effects. The design therefore allowed us to dissociate motor and perceptual learning components. Behavioural data reflected a strict two-choice motor task, while the visual configuration involved four perceptual choices. Learning was evident not only in improved button-press performance but also in anticipatory eye movements, as dwell times in the target AOI increased during the time window preceding stimulus onset (preview window). Although implicit learning occurred as expected, no significant difference emerged between [010] and [011], indicating not only that the alternation advantage had been neutralised, but also that this bias may be perceptually driven, as our manipulation targeted the perceptual (not motor) dimension, although a combined perceptual-motor account cannot be ruled out.

Finally, because [011] occurred more frequently than [010] in the stimulus sequence and carries structural significance within the Fibonacci grammar, it may have become selectively predictable with increased sensitivity to the underlying structure, and learning at point [011] may have benefited from distributional frequency and specific expectations related to parsing. Overall, these findings highlight the importance of understanding the interplay between implicit statistical learning and other cognitive mechanisms.

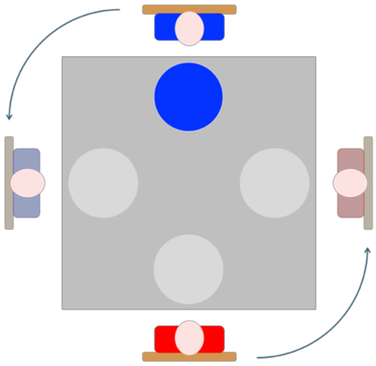


Figure 24. Rotating Design with Four Stimuli Locations

8.1.2 Procedure

The implicit learning protocol employed the following equipment: a Dell 24'' laptop running Windows 11 as operating system, a Tobii Pro Fusion eye-tracker with a sampling frequency of 250 Hz, and a MilliKey^{TM} response box (model MH-5 r1) designed for two-handed use. The eye-tracker was configured using Tobii Pro Eye Tracker Manager, connected to the laptop via a USB Type-C port, and mounted below the display using the provided bracket. The experiment was created and run in Tobii Pro Lab, and a standard calibration routine was performed before testing to generate a 3D eye model for each participant.

The protocol was designed to elicit predictive eye movements while participants performed the modified Serial Reaction Time (SRT) task based on the Fibonacci grammar. The conditions included the deterministic regularities ([01], [110]) and the non-deterministic regularities ([011], [010]). Visual stimuli were binary, blue (0) and red (1), and organised in 534 trials divided into six blocks of 89 trials each (with a pause after Block 3). Each trial consisted of the following sequence (Figure 25): a fixation cross (500 ms), a preview window preceding stimulus onset (2,500 ms) and a stimulus window (max 2,000 ms). If no response was made within 2,000 ms, the programme advanced automatically to the next trial. If a response was made within the stimulus window, the programme directly moved to the fixation cross of the subsequent trial. The visual layout was kept minimal to avoid visual clutter. A grey square located in the centre represented a table, with four circles marking possible stimulus locations. Two stylised players, one red and one blue, sat opposite to each other and rotated 90° anticlockwise after each trial, implementing the rotating design.

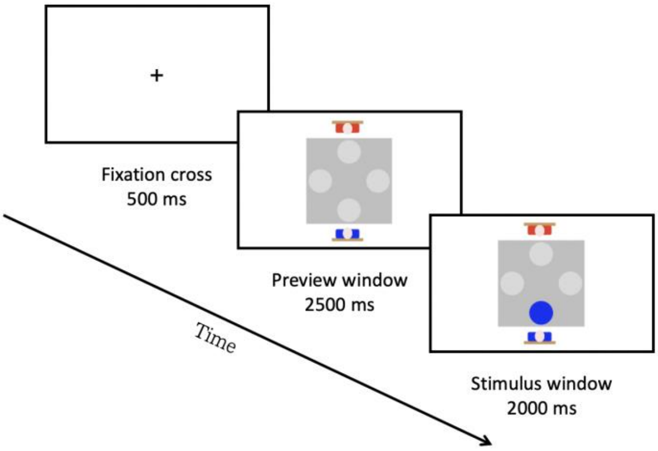


Figure 25. Trial Timeline and Windows

The preview window was crucial for eliciting anticipatory behaviour. During this 2,500-ms interval, no stimulus was present, and gaze data were collected to identify expectations about the upcoming move (red or blue). The stimulus window, instead, captured manual responses: participants pressed the colour-matching button on the response box corresponding to the stimulus displayed on the screen (Appendix 3). The response box was configured in such a way that the red button was on the left, and the blue button was on the right. However, the stimuli could appear in four possible locations, which were coded as congruent (stimulus on the same side of the button), incongruent (stimulus on the opposite side) and vertical (stimulus either in the upper or in the lower location). This manipulation ensured that participants could not rely on simple spatial compatibility mapping, increasing the reliance on sequence-based predictions. Reaction times were measured from stimulus onset to button press. The entire testing session lasted approximately 45 minutes, including a mid-session break (after 267 stimuli) to avoid fatigue.

This setup enabled the simultaneous recording of both behavioural (button-press) and oculomotor (eye-tracking) data, providing complementary measures of implicit statistical learning and allowing the dissociation between strictly motor performance and implicitly constituted knowledge.

8.2 Statistical Analysis

We conducted both within-group and between-group analyses, and for each of the two we examined behavioural outcome measures (accuracy and reaction times) derived from button-press responses, as well as the accuracy of online predictive eye-movements. In particular, behavioural analyses focused on the stimulus window; oculomotor analyses focused on the preview window.

Accuracy of button-press responses was binary-coded and considered only the first button press after stimulus presentation. Reaction times were calculated only for correct trials, measured in milliseconds from stimulus onset to button press, and then log-transformed to reduce skewedness. Accuracy of predictive eye-movements was binary-coded and derived from gaze dwell times, specifically from the relative time spent in each of the competing AOI. AOIs were defined as shown in Figure 26 (see also Vakil et al., 2021): when the players appeared in a vertical configuration, AOIs corresponded to regions above and below an imaginary horizontal midline dividing the screen (Figure 26-A); on the following trial, when the players were arranged horizontally, AOIs dynamically shifted to represent a left-right opposition (Figure 26-B).

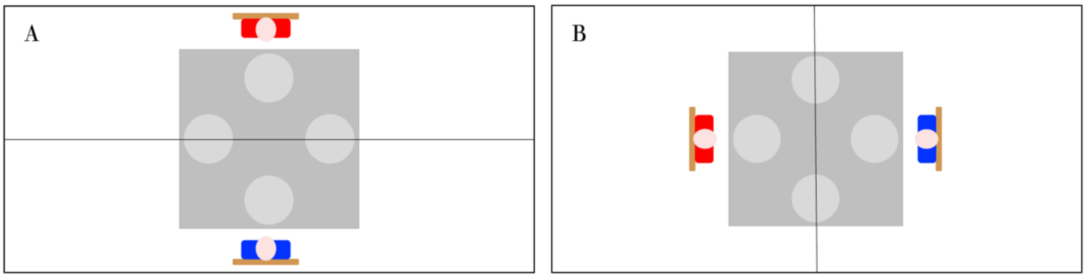


Figure 26. Dynamic AOIs Determination based on Players' Location

All analyses were conducted using R (version 4.4.2). For the behavioural measures, we fitted separate Linear Mixed-Effects Models for each grammar point ([01], [110], [011], [010]), with log RT as the dependent variable, Block (1-6) and Congruency (congruent, incongruent, vertical) as fixed effects, and participant as a random intercept. We also fitted Generalised Linear Mixed-Effects Models (binomial link) with accuracy as the dependent variable, Block (1-6) and Congruency (congruent, incongruent, vertical) as fixed effects, and participant as a random intercept. Where

Block x Congruency interactions emerged, we conducted Bonferroni-adjusted pairwise comparisons using *emmeans*.

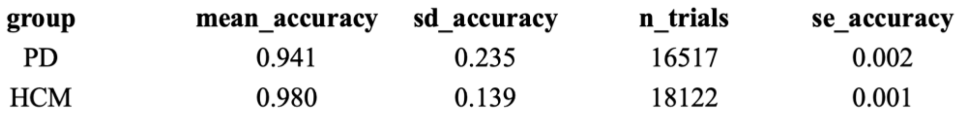
As for eye-tracking models, accuracy of predictive anticipations was modelled with GLMMs (binomial link) using Block and Congruency as fixed effects, and participant as a random intercept. Where appropriate, contrasts were adjusted with Bonferroni correction.

8.3 Results: Within-Group Analyses

8.3.1 Accuracy of Button-Press Responses

Descriptive statistics indicated high overall accuracy in both groups (mean accuracy > .94). The PD group showed the lowest accuracy (94.1% correct), while the HCM group showed near-ceiling performance (98.0% correct). In the PD group, the larger standard deviation suggests greater variability (*SD* = .235) compared to HCM (*SD* = .139) (Table 18).

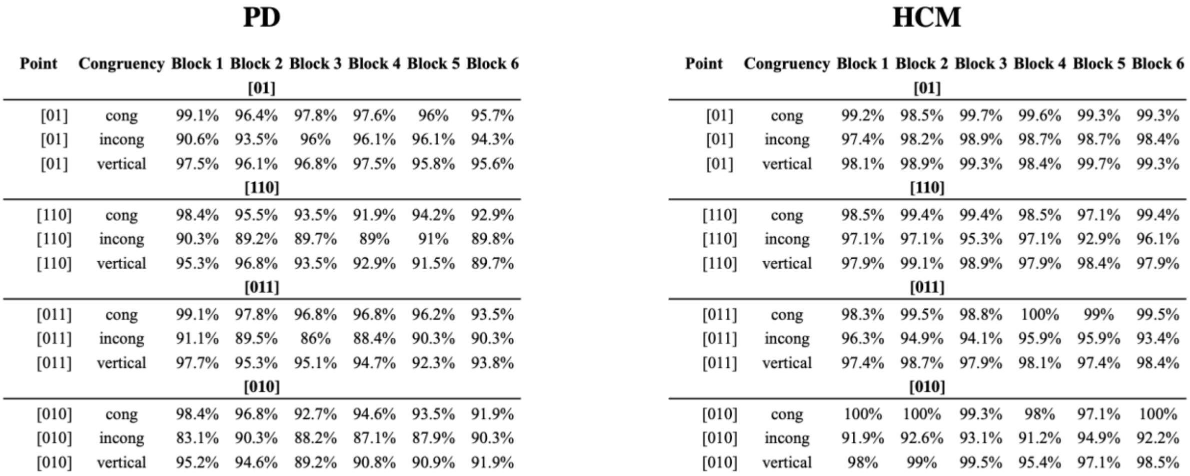
Table 18. Overall Accuracy by Group



group	mean_accuracy	sd_accuracy	n_trials	se_accuracy
PD	0.941	0.235	16517	0.002
HCM	0.980	0.139	18122	0.001

Accuracy rates were then calculated for each group across the twelve experimental conditions, formed by the combination Fib Point ([01], [110], [011], [010]) and Congruency (congruent, incongruent, vertical). Tables 19-20 and Figure 27 present accuracy rates across Blocks for each condition. Overall, accuracy in the PD group was consistently lower than in HCM across all points and congruency conditions.

Tables 19-20. Accuracy per Fib Point x Congruency x Block in PD (left) and in HCM (right)



PD

Point	Congruency	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
[01]							
[01]	cong	99.1%	96.4%	97.8%	97.6%	96%	95.7%
[01]	incong	90.6%	93.5%	96%	96.1%	96.1%	94.3%
[01]	vertical	97.5%	96.1%	96.8%	97.5%	95.8%	95.6%
[110]							
[110]	cong	98.4%	95.5%	93.5%	91.9%	94.2%	92.9%
[110]	incong	90.3%	89.2%	89.7%	89%	91%	89.8%
[110]	vertical	95.3%	96.8%	93.5%	92.9%	91.5%	89.7%
[011]							
[011]	cong	99.1%	97.8%	96.8%	96.8%	96.2%	93.5%
[011]	incong	91.1%	89.5%	86%	88.4%	90.3%	90.3%
[011]	vertical	97.7%	95.3%	95.1%	94.7%	92.3%	93.8%
[010]							
[010]	cong	98.4%	96.8%	92.7%	94.6%	93.5%	91.9%
[010]	incong	83.1%	90.3%	88.2%	87.1%	87.9%	90.3%
[010]	vertical	95.2%	94.6%	89.2%	90.8%	90.9%	91.9%

HCM

Point	Congruency	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
[01]							
[01]	cong	99.2%	98.5%	99.7%	99.6%	99.3%	99.3%
[01]	incong	97.4%	98.2%	98.9%	98.7%	98.7%	98.4%
[01]	vertical	98.1%	98.9%	99.3%	98.4%	99.7%	99.3%
[110]							
[110]	cong	98.5%	99.4%	99.4%	98.5%	97.1%	99.4%
[110]	incong	97.1%	97.1%	95.3%	97.1%	92.9%	96.1%
[110]	vertical	97.9%	99.1%	98.9%	97.9%	98.4%	97.9%
[011]							
[011]	cong	98.3%	99.5%	98.8%	100%	99%	99.5%
[011]	incong	96.3%	94.9%	94.1%	95.9%	95.9%	93.4%
[011]	vertical	97.4%	98.7%	97.9%	98.1%	97.4%	98.4%
[010]							
[010]	cong	100%	100%	99.3%	98%	97.1%	100%
[010]	incong	91.9%	92.6%	93.1%	91.2%	94.9%	92.2%
[010]	vertical	98%	99%	99.5%	95.4%	97.1%	98.5%

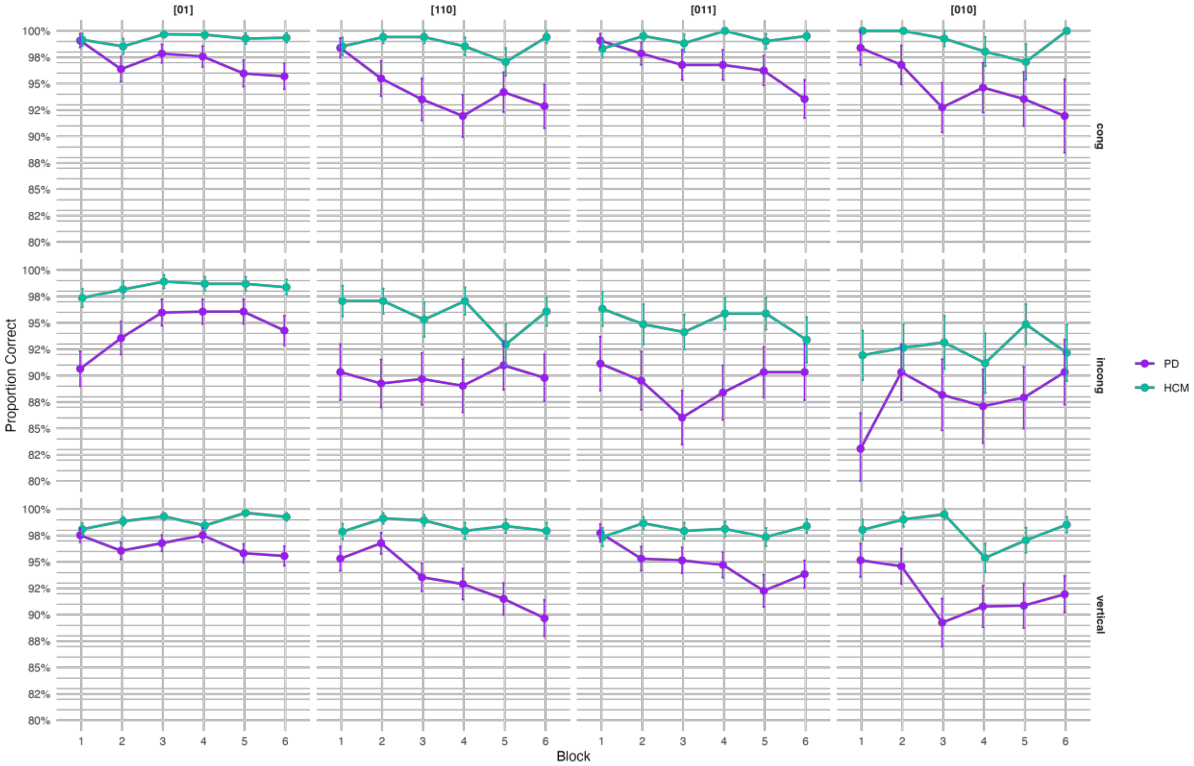


Figure 27. Accuracy (Mean ± SE) across Blocks by Point and Congruency

Note. [0**1**], [11**0**], [01**1**], and [01**0**] correspond to the four transitional regularities that hold within any Fibonacci generation, each of which constituting a separate condition. Notice that Fib Points read based on the last digit, e.g., [01**1**] refers to a [1] that follows [01].

After descriptive analyses, we ran within-group logistic mixed-effects regression models to test whether accuracy fluctuated across Block and Congruency. Separate models were run for each Group and Fib Point, with Block and Congruency (and their interactions) as fixed effects, and participant as a random effect. All models used a binomial link function. Whenever *Block* x *Congruency* interactions were present, Bonferroni-adjusted pairwise comparisons (*emmeans*) were conducted. This approach allowed us to assess whether accuracy varied systematically as a function of task progression and stimulus properties.

8.3.1.1 PD Group

For the PD group at Fib Point [0**1**], the logistic mixed-effects regression showed a significant main effect of *Congruency* but no overall effect of *Block*. A significant Block x *Congruency* interaction was observed, indicating that the effect of Congruency varied across task blocks. We examined simple effects running post-hoc comparisons with Bonferroni correction. In Block 1, accuracy was higher for Congruent than Incongruent trials (p = .0008) and lower for Incongruent than Vertical trials (p < .0001), whereas Congruent and Vertical did not differ (p = .49). From Blocks 2–6, no pairwise differences between *Congruency* conditions remained significant after correction, indicating that the early Congruency differences dissipated with task progression.

At Fib Point [11**0**], a significant main effect of *Block* (Block 2 > Block 1, *p* = .002) and Congruency were observed. A *Block* x *Congruency* interaction emerged again early in the task, with Congruent trials being more accurate than Incongruent trials (Block 1 *p* = .0013; Block 2 *p* = .0330) and Incongruent trials less accurate than Vertical trials (Block 1 *p* = .0474; Block 2 *p* = .0002). *Congruency* effects disappeared in later Blocks. Within Congruent trials, accuracy at Block 1 exceeded that in Block 4 (*p* = .0196) and within Vertical trials, accuracy decreased from Block 1 to Block 6 (*p* = .0148).

At Fib Point [01**1**], significant main effects of *Block* (Block 2 > Block 1, *p* = .0008) and *Congruency* emerged. The Congruent advantage and the Incongruent disadvantage were present and more prolonged compared to previous points, with Congruent trials significantly more accurate than Incongruent trials in Blocks 1–5 (*p* = .0009, .0018, .0006, .0051, .0327) and Incongruent trials less accurate than Vertical trials in Blocks 1–4 (*p* = .0017, .0240, .0002, .0107). Within Congruent trials, accuracy decreased significantly from Block 1 to Block 6 (*p* = .0306), and within Vertical trials from Block 1 to Block 5 (*p* = .0067).

At Fib Point [01**0**], a significant *Block* x *Congruency* interaction was driven by effects in Block 1, in which Congruent trials were more accurate than Incongruent ones (*p* = .0095) and Incongruent trials were less accurate than Vertical ones (*p* = .0002), whereas Congruent and Vertical trials did not differ. From Blocks 2-6, no *Congruency* effects were observed. No overall main effect of *Block* was detected.

Overall, accuracy of the button-press responses in the PD group (Figure 28) was high but showing a robust cost in Incongruent trials. The disadvantage was most pronounced at Block 1, dissipating in later Blocks for points [0**1**], [01**0**], and [11**0**], but persisting through Blocks 1-5 at point [01**1**]. The Vertical condition was generally indistinguishable from the Congruent one after Bonferroni correction. The effect of *Block* was overall small.

8.3.1.2 HCM Group

Moving on to the HCM group, at Fib Point [0**1**] there was no significant *Block* x *Congruency* interaction. Interpreting the main effects, accuracy was lower for Vertical than Congruent trials (β = -0.484, *p* = .0076), while the difference between Congruent and Incongruent showed only a nonsignificant trend (β = 0.42, *p* = .073). *Block* did not show any reliable effect.

At Fib Point [11**0**], the HCM group showed no significant *Block* x *Congruency* interaction. The model revealed a main effect of *Congruency*, with Congruent trials being more accurate compared to both Incongruent (*p* = .0105) and Vertical (*p* < .001) trials. A main effect of *Block* also emerged, reflecting reduced accuracy at Block 5 compared to Block 1 (p = .009), an effect primarily driven by Incongruent trials.

At Fib Point [01**1**], no significant *Block* x *Congruency* interaction emerged in the GLMM. Accuracy remained high across all conditions, with Congruent and Vertical trials near ceiling and Incongruent trials consistently lower throughout the task, although neither *Congruency* nor *Block* reached statistical significance.

At Fib Point [01**0**], no significant *Block* x *Congruency* interaction emerged. Accuracy remained high across all conditions, with Congruent and Vertical trials performing similarly and Incongruent trials slightly lower throughout the task. Neither *Congruency* nor *Block* reached statistical significance.

Overall, accuracy of the button-press responses in the HCM group (Figure 28) was close to ceiling, *Congruency* effects were modest and did not vary systematically across Blocks, and main effects of *Block* were negligible.

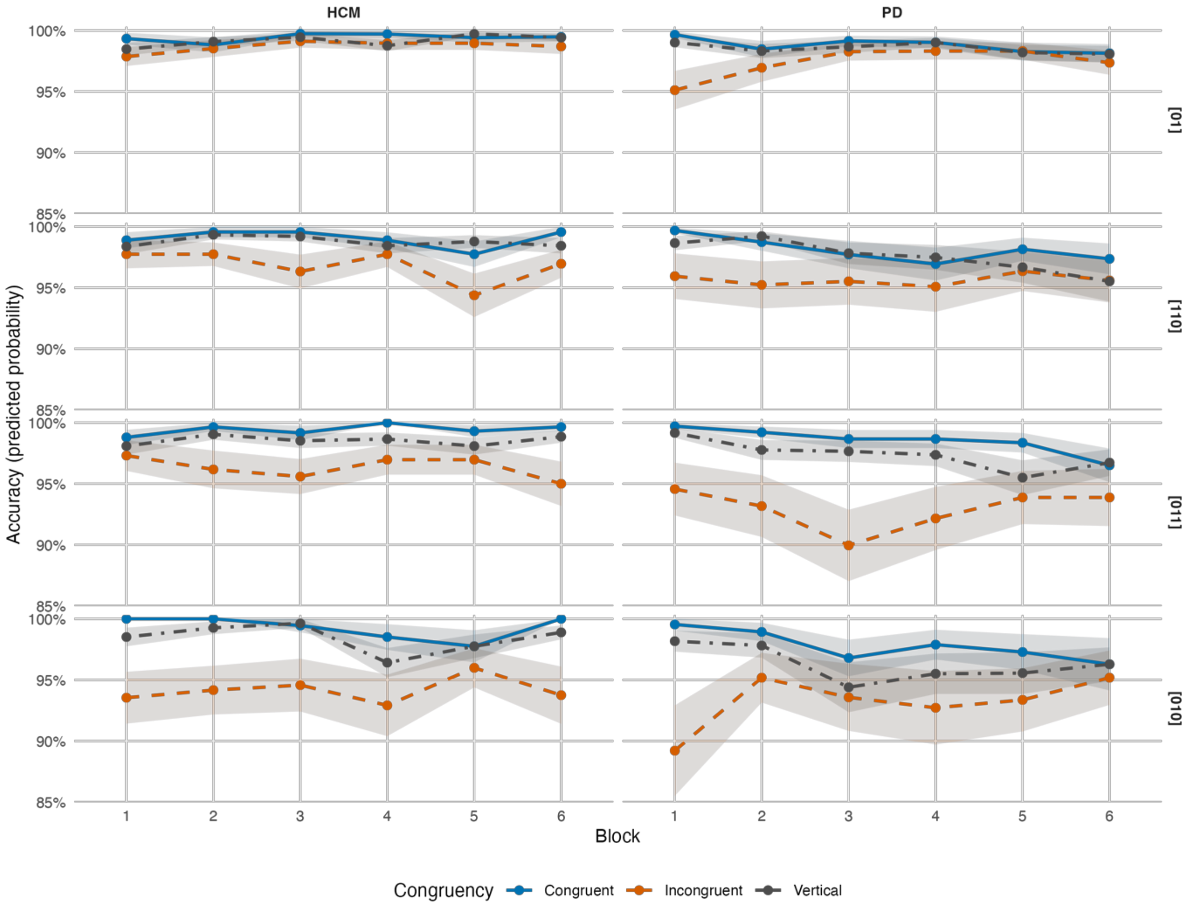


Figure 28. Model Predicted Accuracy by Block and Congruency in HCM and PD

Note. Shaded areas represent 95% confidence intervals (CI) around the model-predicted probability of correct responses.

8.3.2 Reaction Times of Button-Press Responses

Accurate trials entered a series of linear mixed-effect models to evaluate changes in reaction times. For each group separately, *Block* (1-6) and *Congruency* (congruent, incongruent and vertical) were set as within-subject variables, and participant was included as a random intercept. Whenever Block x Congruency interactions were present, Bonferroni-adjusted pairwise comparisons were performed using the *emmeans* package. Figure 29 displays the model-predicted reaction times across Blocks, Congruency conditions and Fib Points for both groups.

8.3.2.1 PD Group

At Fib Point [01], the linear mixed-effects model revealed significant main effects of both *Block* and *Congruency*. Reaction times were substantially slower for Incongruent than Congruent trials ($\beta = +114.7$ ms, $p < .001$) and for Vertical relative to Congruent trials ($\beta = +74.7$ ms, $p < .001$). Reaction times modestly decreased across blocks, with significantly faster responses at Block 4 compared to Block 1 ($p = .0047$), suggesting that learning of the [01] regularity occurred. Other block differences were nonsignificant. The *Block* x *Congruency* interaction did not reach significance ($p = .107$), indicating that the *Congruency* effect remained stable across task progression.

At Fib Point [110], the model showed a reliable main effect of Congruency ($p < .001$), which did not significantly interact with Block. Incongruent and vertical trials were again slower than congruent ones, and no systematic reduction in reaction times was detected across blocks.

At Fib Point [011], both main effects reached significance, and a weak Block x Congruency interaction also emerged, reflecting prolonged interference for incongruent trials that gradually diminished over the final blocks.

At Fib Point [010], reaction times followed the same pattern, with a main effect of Congruency but no Block effect and no interaction.

Overall, the PD group displayed consistently slower responses and a robust cost for incongruent and vertical trials. Practice-related acceleration was minimal. These results parallel the accuracy pattern and highlighting a Congruency cost in PD and a reduced learning as measured through motor execution.

8.3.2.2 HCM Group

At Fib Point [01], the LMM indicated a significant main effect of Congruency ($p < .001$), with incongruent trials slower than both congruent and vertical ones, while the Block x Congruency interaction was not significant. Mean reaction times decreased across blocks, suggesting a general learning during task progression.

At Fib Point [110], both Block and Congruency were significant, with responses becoming faster over time and incongruent trials remaining slower than congruent ones. No interaction was found.

At Fib Point [011], the Congruency main effect persisted, but the Block effect was weaker and the interaction not significant.

At Fib Point [010], no main effect of Block and no interaction emerged. A marginal main effect of Congruency indicated that incongruent trials were tendentially slower.

Overall, reaction times in the HCM group showed a stable improvement across blocks for the two deterministic rules [01] and [110]. A tendency for reduction in reaction times was also present for the non-deterministic point [011], indicating sensitivity to stimulus regularities. Congruency effects were modest, indicating an efficient adaptation during the task on behalf of this group.

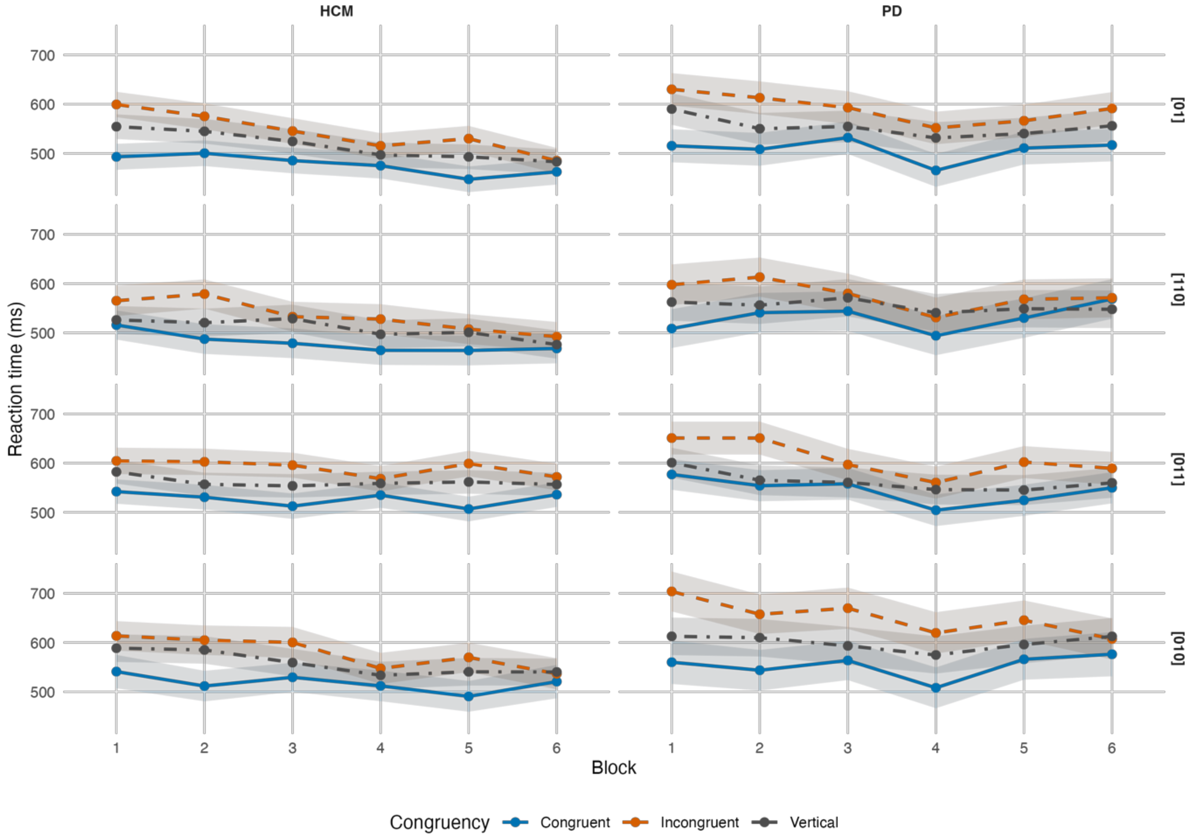


Figure 29. Model Predicted RT by Block and Congruency in HCM and PD

Note. Shaded areas represent 95% confidence intervals (CI) around the model-predicted reaction times.

8.3.3 Accuracy of Predictive Eye Movements

Accuracy of predictive eye movements was defined as the proportion of trials in which participants' gaze dwelt longer in the AOI corresponding to the upcoming stimulus during the preview window. As done for button-press data, we first conducted within-group analyses. For each Group (PD, HCM) and Fib Point ([01], [110], [011], [010]) separately, we fitted logistic mixed-effects models with Block (1-

6) as a fixed effect and participant as a random intercept. Model-predicted probabilities and pairwise comparisons between Blocks (Bonferroni-corrected) are reported below and summarised in Figure 30.

8.3.3.1 PD Group

Across all Fib Points, the PD group showed relatively flat trajectories of predictive accuracy over Blocks, with probabilities generally clustering around chance and no reliable evidence of improvement over task progression.

At Fib Point [01], the GLMM revealed a significant intercept (β = -0.33, $p < .001$), indicating that overall predictive accuracy remained below the logit midpoint (i.e., tended to be lower than .50). Block did not exert a robust effect on predictive gaze behaviour. Model-predicted probabilities ranged from approximately .38 in Block 1 to .44 in Block 6, and none of the pairwise Block comparisons survived Bonferroni correction. Thus, despite some numerical increase in later Blocks, anticipatory fixations in the PD group did not show a systematic learning-related gain for the deterministic [01] rule.

At Fib Point [110], neither the intercept nor the Block predictors reached significance. Predicted probabilities were attested between .52 and .56 across Blocks, with no clear trend and no significant pairwise differences after correction. This pattern suggests that, for this second deterministic point, PD participants' anticipations remained essentially stable over time, with no clear indication of incremental improvement in predictive gaze.

A similar picture emerged at the probabilistic point [011]. None of the Block coefficients reached statistical significance. Predicted probabilities fluctuated between .53 and .57, and Bonferroni-adjusted pairwise comparisons again failed to reveal any systematic contrasts between early or late Blocks. PD participants did not exhibit any strengthening of anticipatory eye movements at this point.

Finally, at Fib Point [010], the model indicated no significant effects of Block. Predicted probabilities ranged between .36 and .43, and Block-wise contrasts were non-significant after correction. Thus, PD participants showed no evidence of improved prediction, as no tendency to drift toward the correct AOI was recorded.

Taken together, within-group analyses in the PD sample indicate that anticipatory oculomotor behaviour remained largely stable across Blocks and close to chance across all Fib Points. Unlike button-press measures, which showed some sensitivity to Congruency and improvement over task progression, predictive eye movements in PD did not exhibit clear signatures of incremental learning of either deterministic or probabilistic Fibonacci-generated regularities.

8.3.3.2 HCM Group

In contrast, the HCM group showed clear changes in predictive eye movements over task progression at several Fib Points, particularly for deterministic regularities.

At Fib Point [01], the GLMM revealed robust effects of Block. Compared to the reference Block, later Blocks were associated with high accuracy (block4: $\beta = 0.18$, $p = .001$; block5: $\beta = 0.46$, $p < .001$). Model-predicted probabilities increased steadily from about .40 in Block 1 to approximately .65 in Blocks 5-6. Bonferroni-corrected pairwise comparisons confirmed that predictive accuracy in Blocks 3-6 was significantly higher than in Blocks 1-2 (all $p \leq .004$), with additional differences between intermediate and late Blocks (e.g., Block 3 < Block 5, $p < .001$). These results indicate robust learning of the [01] transition in the eye-movement domain for neurotypical individuals.

At Fib Point [110], a similar pattern emerged, albeit less pronounced. Block effects were again significant, with early Blocks showing reduced predictive accuracy relative to later ones (block1: $\beta = -0.23$, $p = .002$; block2: $\beta = -0.25$, $p < .001$). Predicted probabilities increased from around .56 in Block 1 to almost .69 by Blocks 5-6. Pairwise comparisons indicated that accuracy in Blocks 4-6 was significantly higher than in Blocks 1-2 and Block 3 ($p \leq .04$), suggesting that HCM participants progressively learned the regularity [110].

For the probabilistic point [011], by contrast, no evidence of learning was observed. Block was not significant, and predicted probabilities remained remarkably stable around .50-.54 across the entire task. Pairwise comparisons yielded no significant differences between Blocks after Bonferroni correction. Thus, for this locally ambiguous point, predictive eye movements in HCM did not show a clear increase.

At Fib Point [010], the GLMM again showed a significant Block effect. Early Blocks were associated with reduced predictive accuracy, whereas Block 4 showed a significant improvement ($\beta = 0.29$, $p = .001$). Predicted probabilities rose from about .42-.43 in Blocks 1-2 to approximately .55 in Block 4 and stabilised around .50 in Blocks 5-6. Pairwise comparisons confirmed that predictive accuracy at Block 4 was significantly higher than in Block 1 and 2 (both $p \leq .003$), while differences among the later Blocks were no longer reliable. These findings suggest that HCM participants were able to develop anticipatory sensitivity also for Point [010].

Overall, the oculomotor data in the HCM group indicate that predictive eye movements were highly sensitive to almost all Fibonacci regularities. Predictive accuracy increased markedly across Blocks at [01] and [110] and showed a more modest but reliable improvement at [010], whereas no learning was detected at [011].

It is important to note, however, that the interpretation of non-deterministic Fib Points requires particular caution. These points are, by definition, not fully predictable, and this makes behavioural and oculomotor performance more delicate to interpret. Among the two probabilistic transitions, HCM participants performed noticeably worse at [011] compared to [010], whereas PD participants showed lower accuracy at [010] relative to HCM (as further detailed in the between-group comparisons in the next section). We simply acknowledge these two observations together with the fact that, within the Fibonacci grammar, [010] is less frequent than [011]. Beyond these descriptive patterns, it would be inappropriate to draw strong conclusions about how PD participants process probabilistic points, because even in neurotypical individuals the mechanisms supporting improvements at probabilistic points remain unclear. For these reasons, the discussion that follows will consider all Fib Points but will place particular emphasis on the deterministic transitions, for which learning trajectories are more interpretable.

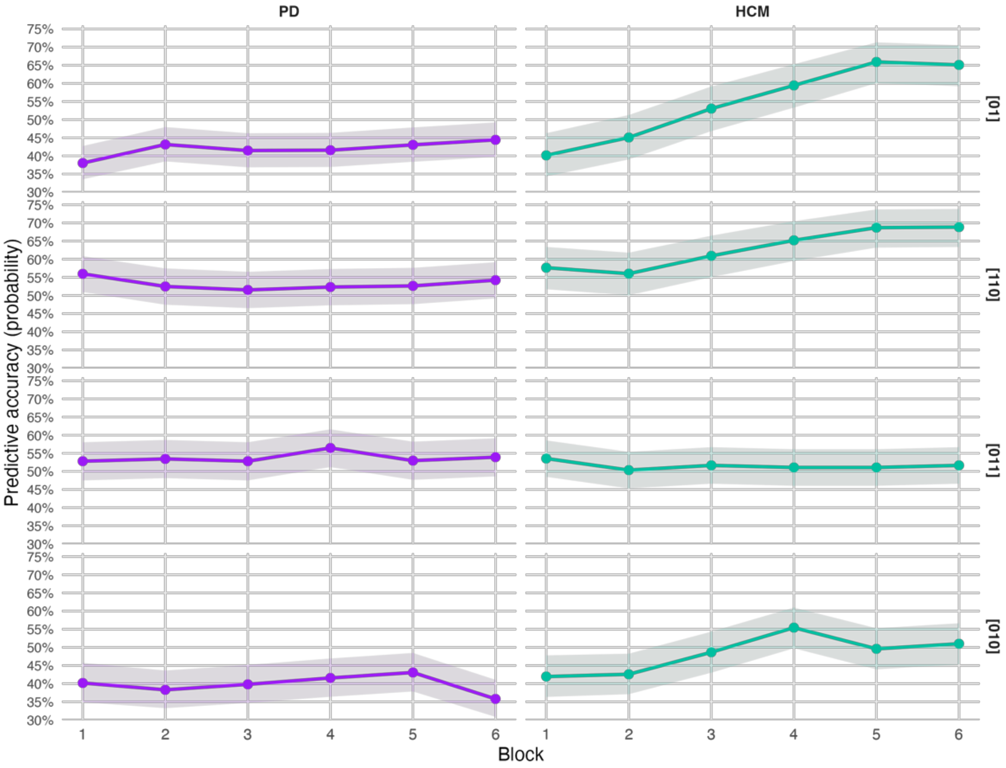


Figure 30. Model-Predicted Anticipatory Dwell Accuracy by Block in PD and HCM

Note. Shaded areas represent 95% confidence intervals (CI) around the model-predicted probability of correct anticipatory dwell responses.

When considered alongside the motor results, these findings suggest that neurotypical individuals rapidly internalised the regularities of the sequence of stimuli and expressed this knowledge through increasingly accurate anticipatory gaze behaviour, whereas individuals with PD did not show comparable gains in predictive eye movements during task progression.

8.4 Results: Between-Group Analyses PD vs. HCM

8.4.1 Accuracy of Button-Press Responses

To directly compare people with PD and controls, we fitted a mixed-effects logistic regression model with Accuracy as dependent variable, and Group (PD, HCM), Fib Point ([01], [110], [011], [010]), Block (1-6) and Congruency (congruent, incongruent, vertical) as fixed effects, with participant as a random intercept.

Across the task, the model revealed a significant main effect of Group (β = -0.38, p = .006), indicating that PD participants were overall less accurate than HCM. The global disadvantage is also visible in the descriptive statistics, where PD consistently showed lower mean accuracy than HCM at all Fib Points and Congruency levels. Crucially, however, this between-group difference was modest in size and did not systematically vary with specific combinations of Fib Point and Block. There was no evidence of a robust Group x Fib Point x Block interaction, suggesting that the relative disadvantage of PD remained fairly stable across the sequence and did not selectively emerge at particular stages of task progression or at specific points.

Descriptively, group differences were most pronounced under the incongruent condition, in which stimulus and response locations were spatially reversed. In this condition, PD participants consistently showed slightly reduced accuracy compared to HCM, whereas in congruent and vertical trials the two groups were almost indistinguishable, with accuracy close to ceiling throughout the task. Model-predicted probabilities, collapsed across Congruency, are displayed in Figure 31, and illustrate a small but persistent accuracy cost in PD relative to HCM across Fib Points and Blocks.

Taken together, between-group analyses of button-press accuracy indicate that, although both groups performed at high levels overall, individuals with PD exhibited a consistent but subtle decrement in accuracy compared to matched controls. This disadvantage was more evident in mode demanding (incongruent) trials and became statistically reliable at a limited number of Fib Point x Block combinations (Figure 31).

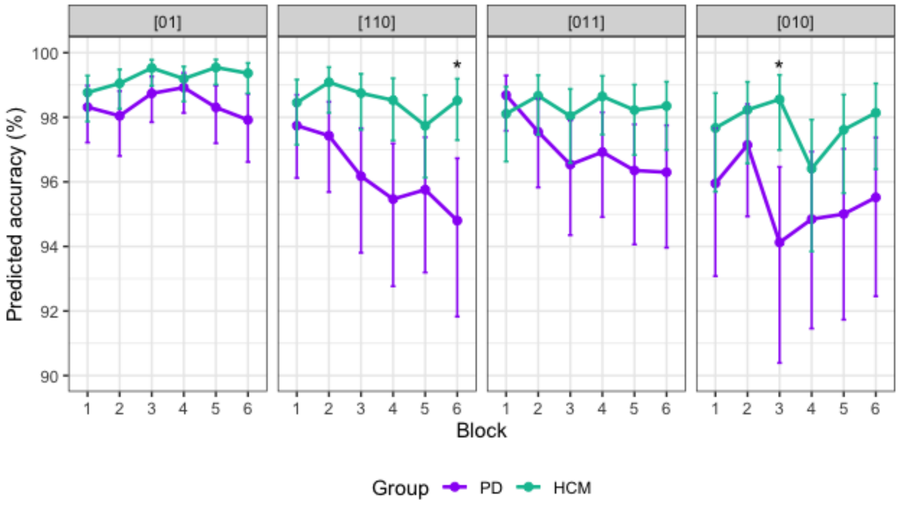


Figure 31. Model-Predicted Accuracy of Button-Press Responses by Block and Point (PD vs. HCM)

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

8.4.2 Reaction Times of Button-Press Responses

Between-group differences in motor speed were assessed with a linear mixed-effects model on log-transformed reaction times from correct trials only. The model included Group (PD, HCM), Fib Point ([01], [110], [011], [010]), Block (1-6), and Congruency (congruent, incongruent, vertical) as fixed effects, and a random intercept for participant.

At the global level, no main effect of Group emerged: PD and HCM showed overall comparable reaction times ($p = .33$). In contrast, robust main effects of Fib Point, Block, and Congruency were observed. Consistent with the within-group analysis, reaction times differed across Fib Points, with some points being generally slower than the reference point [01]. Early Blocks were reliably slower, while later Blocks showed reduced latencies, indicating learning-induced speeding in both groups. Congruency exerted a strong effect, with incongruent trials being the slowest, congruent trials the fastest, and vertical trials occupying an intermediate position.

Several Group x Fib Point and Group x Block interactions reached significance at the model level, suggesting that the difference between PD and HCM may vary somewhat across specific combinations of points and block. However, when we examined these patterns more directly using estimated marginal means, pairwise PD-HCM contrasts were small and never survived correction for multiple comparisons. On the log scale, PD participant tended to be slightly slower than HCM (differences on the order of 0.02-0.08 log units), but all Bonferroni-adjusted p-values were $\geq .52$ across all Fib Point x Block combinations. When back-transforming latencies into milliseconds, the corresponding differences ranged approximately between 15 and 80 ms, with confidence intervals consistently overlapping zero and no contrast remaining significant after Bonferroni correction.

Figure 32 illustrates these results. Across all Fib Points, the predicted reaction time trajectories for PD and HCM are surprisingly largely overlapping. Both groups showed similar speeding over Blocks, particularly at the deterministic points [01] and [110], and exhibited comparable Congruency effects. Taken together, these results indicate that, on accurate trials, motor execution speed is broadly comparable in PD and HCM, and that the between-group differences observed in accuracy are not mirrored by any robust difference in terms of reaction times.

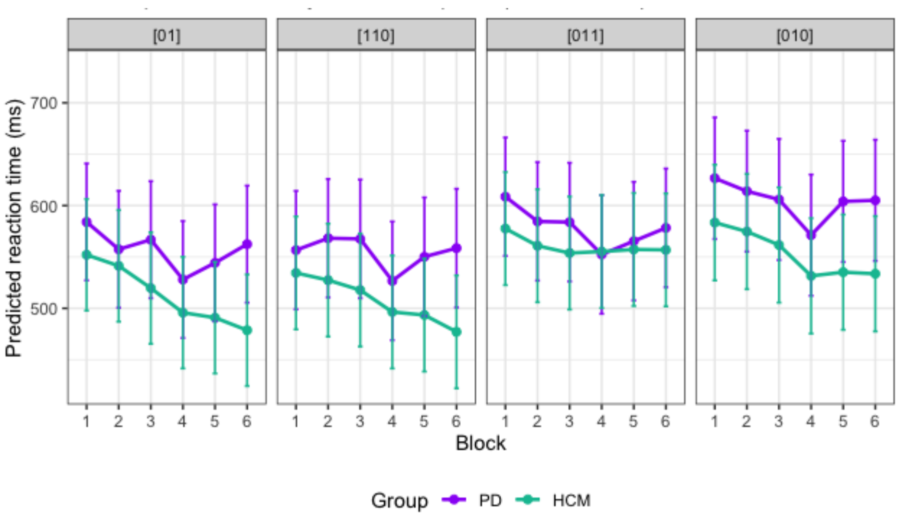


Figure 32. Model-Predicted RT of Button-Press Responses by Block and Point (PD vs. HCM)

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

8.4.3 Accuracy of Predictive Eye Movements

Between-group differences in anticipatory gaze behaviour were examined using a binomial GLMM including Group (PD, HCM), Fib Point ([01], [110], [011], [010]) and Block (1-6) as fixed effects, with participant as a random intercept. This model assessed whether the two groups differed in their ability to anticipate upcoming stimuli during the preview window.

The model results are illustrated in Figure 33. This model revealed a significant main effect of Group, with PD participants showing overall lower predictive accuracy than HCM. In addition, several Group x Fib Point, Group x Block, and Group x Fib Point x Block interactions reached significance, indicating that the magnitude of the group difference varied across points and blocks of the task. To characterise these effects, we computed estimated marginal means and pairwise contrasts between PD and HCM for each Fib Point x Block combination, applying Bonferroni correction across comparisons.

Pairwise comparisons showed no reliable group differences in the earliest stages of the task (Blocks 1-2), where all odds ratios were close to 1 and none of the contrasts reached significance (all $p \geq .26$). All reported *p*-values from pairwise contrasts are Bonferroni-corrected. From Block 3 onwards, however, robust and systematic group differences emerged at the deterministic points. At [01], PD participants had significantly lower odds of making a correct prediction than HCM in Blocks 3-6 (all $p < .0001$). A similar pattern was observed at [110], where PD again showed reduced predictive accuracy in Blocks 3-6 ($p \leq .0054$). These values indicate that, in the second half of the task, the odds of anticipating the correct AOI in PD were approximately 30-60% lower than those of HCM at deterministic transition points. Because [01] and [110] are the only fully predictable transitions in the Fibonacci sequence, these contrasts provide the strongest test of rule-based predictive learning.

At the probabilistic point [010], group differences were somewhat smaller but still evident in several blocks. PD participants showed significantly reduced predictive accuracy relative to HCM in Blocks 3, 4 and 6 ($p = .0216, .0003, .0001$, respectively). In contrast, no PD-HCM differences emerged at the other probabilistic point [011] in any block (all $p \geq .12$).

Taken together, these between-group analyses show that anticipatory gaze behaviour is broadly intact and improves over time in HCM but remains substantially impaired in PD, particularly from Block 3 onwards. While early in the task the two groups are indistinguishable, as regularities are gradually internalised by controls, PD participants fail to show a corresponding increase in predictive accuracy. These findings converge with the within-group analyses, indicating that PD participants do not translate exposure to deterministic regularities into robust anticipatory eye movements, even when such regularities are successfully exploited at the motor level.

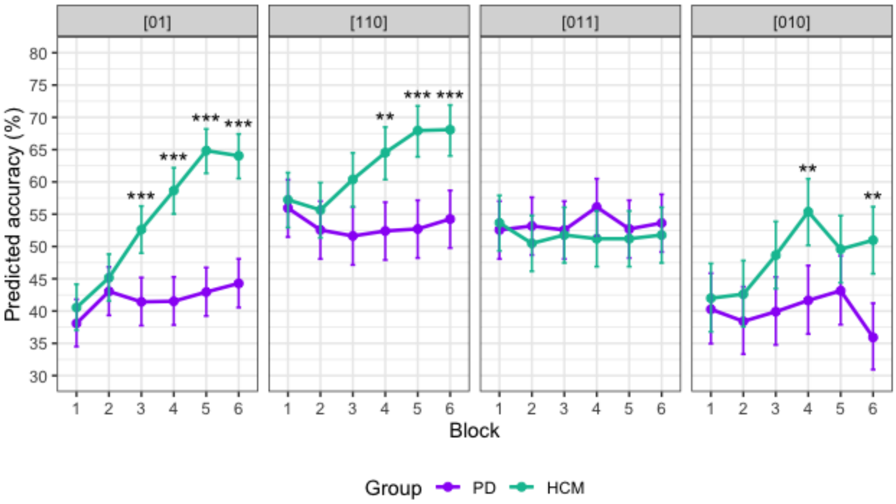


Figure 33. Model-Predicted Dwell Accuracy by Block and Point (PD vs. HCM)

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

8.5 Discussion

The present study examined implicit statistical learning (ISL) in PD using a combined behavioural-oculomotor paradigm designed to disentangle motor execution from predictive processing. By pairing a modified Serial Reaction Time (SRT) task with eye-tracking focusing on anticipatory eye movements, we assessed whether individuals with PD implicitly acquire the regularities holding in Fibonacci-generated sequences of stimuli and whether this learning manifests at both motor and perceptual-predictive levels.

The pattern that emerges from our finding is not a uniform deficit but a system-specific dissociation. PD participants demonstrated preserved learning when performance relied primarily on motor execution, while they showed a marked reduction in predictive gaze behaviour. This dissociation provides important insights about the cognitive and neural mechanisms underlying implicit learning in PD.

8.5.1 Learning Deterministic vs. Non-Deterministic Regularities

A central objective of the study was to determine whether individuals with PD would acquire the two deterministic rules of the Fibonacci grammar, namely the points [01] and [110], where the last digit is fully predictable. Deterministic points provide the strongest test for true rule internalisation: if participants have abstracted the underlying regularity, these are precisely the points they should be able to anticipate with high precision.

Neurotypical controls exhibited exactly this pattern. Their eye movements showed progressive and robust increases in anticipatory accuracy, mirroring behavioural learning and indicating that they succeeded in internalising the underlying rules.

PD participants, by contrast, did not show this shift towards predictive oculomotor behaviour. Although they responded correctly in the motor task, their gaze behaviour remained close to chance and failed to improve over blocks, even for the deterministic regularities that participants typically learn most easily. This suggests that PD participants did not consolidate the rules sufficiently to generate predictions, even though their behaviour indicates some familiarity with the regularities in terms of button-press accuracy and latency.

When turning to the non-deterministic points ([010] and [011]), interpretation must be more cautious because none of the two points is fully predictable. Two descriptive patterns emerged: HCM performed less accurately at [011] than at [010], while PD participants showed lower performance at [010] compared to HCM. These differences may reflect frequency within the Fibonacci grammar, as [011] appears more often than [010]. However, because even neurotypical participants did not consistently develop anticipatory advantages at probabilistic points, it is not meaningful to conclude that PD participants have selective impairments here. The more informative deficits lie precisely where predictability is maximal, namely the deterministic points, where PD participants should have shown clear learning but did not.

8.5.2 Motor vs. Predictive Learning: Evidence for a Dissociation

One of the most important findings is the clear divergence between motor learning and perceptual-predictive learning. Despite the known motor deficits in PD, reaction times did not differ significantly between PD and HCM. Both groups improved modestly over blocks, and the magnitude of this improvement was similar. This shows that motor impairment did not prevent PD participants from learning to respond correctly. They could react to the stimulus efficiently by extracting low-level information to respond accurately and improve over time. This finding is theoretically important: it shows that pure motor limitations do not explain the reduced learning observed at the predictive level.

In contrast, predictive gaze behaviour was consistently impaired in PD, both at deterministic and probabilistic points. PD participants did not transition from reactive responding (stimulus window) to anticipatory processing (preview window). This suggests that while PD participants can learn within a motor response system, they struggle to transfer the extracted regularities to a predictive perceptual system. What is compromised is not the acquisition of surface-level patterns, but the integration of perceptual information with an internal predictive model (a process that relies on frontostriatal connectivity). The difficulty in PD is not learning nor is its motor execution: it is the transition between systems. PD participants can learn enough to act correctly in a reactive fashion, but they do not build or deploy a predictive internal representation of the regularities. The consequence is that the resulting learning is sufficient for motor execution and stimulus-driven behaviour, but insufficient for perceptual and prediction-driven behaviour, and the shift between the two appears compromised in PD.

8.5.3 Theoretical Implications

Together, the findings contribute a refined understanding of how implicit learning operates in PD. PD does not entail a global deficit in learning regularities, but rather a selective impairment in predictive processing. Learning at the motor level is preserved, but learning does not propagate across systems to support anticipation. This supports a multi-component view of implicit learning, in which different cognitive systems, perceptual, motor, predictive, can be differentially affected by pathology. The present study therefore provides novel evidence for the striatal dependence of predictive statistical learning, and shows that anticipatory oculomotor behaviour may offer a sensitive window onto the cognitive consequences of dopaminergic loss. In particular, the absence of predictive learning in PD is consistent with the known role of the basal ganglia in incremental, feedback-driven learning, the sensitivity of probabilistic and predictive tasks to dopaminergic loss, and findings that dopaminergic modulation (e.g., STN stimulation) can selectively improve the learning of weak associations (Wilkinson et al., 2011). The predictive deficit observed here may thus reflect reduced dopaminergic signalling within basal ganglia pathways critical for generating internal models of upcoming events.

8.6 Summary and Conclusions

The present study investigated implicit statistical learning in PD using a combined motor-oculomotor paradigm based on the Fibonacci grammar. This design allowed us to examine learning at two levels: motor execution (button-press accuracy and reaction times) and predictive processing (anticipatory eye movements).

Across behavioural measures, PD participants were generally accurate and showed improvements in performance over the course of the task. Reaction times did not differ significantly from those of neurotypical controls, demonstrating that motor impairment did not interfere with learning within the task-specific motor demands.

However, a different pattern emerged for predictive eye movements. Neurotypical controls showed robust anticipatory gaze behaviour, particularly for the deterministic regularities, indicating internalisation of the underlying transitional probabilities. In contrast, PD participants did not show such predictive shifts. Their anticipatory accuracy remained near chance and did not improve across blocks, even at points where predictions were entirely deterministic.

This dissociation between preserved motor learning and impaired predictive gaze behaviour suggests that PD selectively disrupts the predictive component of implicit learning, likely reflecting striatal dysfunction and reduced dopaminergic modulation of predictive coding mechanism. Importantly, the deficit does not lie in learning *per se*, nor in motor execution. Rather, it emerges at the point where information must be transferred from a low-level motor system to a higher-level cognitive system that supports prediction. PD participants can encode regularities well enough to support motor improvements in terms of reactive behaviour, but the recoding of motor-based input into an abstract, cognitively accessible predictive representation appears compromised. This breakdown in system-to-system transfer provides a principled explanation for the selective impairment of anticipatory gaze.

Together, these findings refine our understanding of implicit learning in PD and demonstrate the value of eye-tracking as a sensitive measure capable of revealing learning-related processes that may remain invisible in traditional behavioural paradigms.

PART III – GENERAL DISCUSSION

Chapter 9 – Bridging Language and Implicit Learning Results in PD

In this dissertation three experimental studies examined linguistic and implicit learning processes in individuals diagnosed with Parkinson's disease (PD; $N = 31$) and neurotypical controls (HCM; $N = 34$). Study 1 evaluated lexical access and semantic-morphosyntactic integration using a picture naming paradigm (Chapter 6). Study 2 focused the investigation on derivational morphology through an elicited-production paradigm targeting deverbal nominalisation (Chapter 7). Study 3 shifted to a domain-general mechanism, implicit statistical learning, employing a combined button-press and eye-tracking paradigm based on the Fibonacci artificial grammar (Chapter 8).

Across all three studies, a theoretical revealing picture emerges: PD does not compromise conceptual knowledge, action-related semantics, or lexical categories wholesale. Instead, it selectively disrupts the transmission of information across representational systems, that is, the interface where conceptual structure must be integrated with other processes, such as morphosyntactic, morphological, or predictive/computational processes. This interface-level vulnerability emerged across different domains: in recalling lexical items of covert causation (Study 1), in derivational morphology, which requires rule-based computations (Study 2), and in implicit learning, where a transition of the learned regularities is required from motor execution into anticipatory predictions (Study 3).

This concluding chapter summarises the main empirical contributions emerging from Part II. It highlights the convergences across studies and provides evidence for a "system-to-system" deficit in PD. Additionally, it examines the theoretical implications and locates these novel findings in the broader context of existing literature. Predictive prospects and directions for future work will also be outlined.

9.1 Overview of the Main Results

In Study 1, which revolved around lexical access and semantic competence in PD, we probed the efficient retrieval of nouns and verbs as measured through accuracy and latencies. We operated in a context where the literature has been reporting fascinating insights about the potential interaction between movement impairment in PD and a selective impairment of movement-related items that spanned across both verbs and nouns when recruiting conceptual features such as "motion" for verbs and "manipulability" for nouns (Herrera et al., 2012; Bocanegra et al., 2017; Johari et al., 2019a), such that a verb like "to dance" was found to be more impaired than "to read" and a noun like "screwdriver" was more challenging than "mountain" (Chapter 2). These accounts are captivating. They provide evidence for theories of embodied cognition, maintaining that language-related processes are grounded in physical experiences (Lakoff & Johnson, 1999; Barsalou, 1999, 2008), to the point that disruption of the motor system in PD might lead to a parallel impairment of the linguistic system.

A key unresolved issue by the existing literature is where in the process of lexical retrieval PD-related deficits are located. On one hand, the impairment might be at the conceptual representation level, and this would be consistent with the embodied cognition views referred to in the previous literature; on the other hand, the deficit might be located at one of the steps following conceptual activation (cf. models of lemma production, Chapter 2, section 2.4.2) and entering the language system, thus involving lexical selection, morphosyntactic encoding. These two perspectives allowed us to shed light on the locus of impairment by opposing a conceptual locus and a specifically linguistic locus.

To probe whether and at which of the two loci impairment took place in PD, we manipulated nominal and verbal stimuli based on conceptual features and linguistic features, and operationalised in picture naming. In particular, the manipulated conceptual feature was what we termed "action-relatedness", a score of conceptual action involvement we obtained by means of an independent rating study ($N = 20$) in which neurotypical young individuals rated each stimulus on a 9-point Likert scale. The manipulated linguistic features were argument structure and agentivity for verbs, the latter operationalised according to Reinhart's Theta System (2002), which encompasses traits operationalised at the interface between concepts and language, and telicity and qualia structure for nouns, according to Pustejovsky's framework (1991, 1995). This dual manipulation allowed us to assess whether naming deficits in PD reflect impairment at the level of conceptual action-relatedness or at the level of the linguistic structure, or at their interaction.

Results of Study 1 were as follows (Chapter 6). For nouns, reaction times revealed PD-related slowing, but action-related nominal items *facilitated* naming in the PD group. This result is at odd with previous literature highlighting action-related impairment, while in the present experiment the opposite trend was observed, a pattern which was not present in the control group. On the contrary, nouns ascribed to the category of "artefacts" induced greater slowing in PD. This category, encompassing items such as "footprint", "signature", "wound", "bite", "shadow", "embroidery", "tattoo", includes entities that are results of actions. These items are specifically associated with an implied causal structure, since a prior event or agent produced the entity, but such causal/movement/intentional component is covert. Accuracy was largely preserved in PD suggesting intact lexical-semantic representations, except from the category depicting geometrical "shapes", likely attributable to set-shifting requirements within the task and not to a degraded representation. As far as verbs are concerned, a similar pattern emerged, though with a slightly different profile. Accuracy again remained high and broadly comparable between groups once lexical and perceptual covariates were controlled for, indicating that core verb representations are largely preserved in PD. The differences surfaced in the reaction times results. Individuals with PD were consistently slower than controls, and this slowing was not homogeneous across verb classes. It was particularly pronounced for "transitive accomplishments" and for "unergative" verbs, especially for "unergatives with internal agentivity", whereas "unaccusatives" and "transitive achievements" showed only trend-level differences. In other words, verb forms whose argument structure encodes richer, internally caused or volitional dynamics were retrieved more slowly in PD than in controls. Crucially, this pattern did not reduce to a simple effect of "motion content": action-relatedness as an independent predictor did not systematically explain the group differences, not did a binary distinction in agentivity. Rather, difficulty emerged precisely where agentive and causal features had to be encoded through particular argument-structure templates, such as internally caused unergatives, suggesting that the bottleneck lies in the linguistic instantiation of those conceptual features rather than in the availability of action-related concepts themselves.

Overall, Study 1 therefore suggests that lexical access in PD is best understood as a disorder of integration rather than storage. Conceptual knowledge, including action-related semantics, appears broadly preserved and can even show a facilitative effect, as in the faster naming of highly actional nouns in PD. By contrast, linguistic configurations that require the embedding of covert causation or mental involvement/intentionality into morphosyntactic structure, such as "artefacts" nouns or internally agentive verbs, disproportionately tax the system and manifest as selective slowing in reaction times. This profile fits naturally with an interface-level embodiment view (Caramazza et al., 2014), in which the difficulty does not reside in "embodied concepts" themselves, but in the processes that make them legible to the linguistic system.

Study 2 (Chapter 7) extended this picture by shifting the focus from lexical access to derivational morphology, and in particular to deverbal nominals, which sit exactly at the intersection we were interested in: grammatically, they are nouns but internally, they retain verbal event structure and argument structure. They therefore offer an ideal testing ground to ask whether the vulnerabilities identified in Study 1 extend to the morphological operations that code verbal content into nominal format. The elicited-production paradigm required participants to derive either a verb from a deverbal nominal prime or a deverbal noun from a verbal prime, and in the second part to produce either simplex or morphologically complex event nouns that were as close in meaning as possible.

The results again pointed away from a category-wide noun-verb dissociation as well as from a purely conceptual locus of impairment. In terms of grammatical class, PD participants did not show a systematic disadvantage for verbs as compared to deverbal nominals or vice versa. Action-relatedness by itself also did not lead to worse performance. On the contrary, as in Study 1, action-related material tended to be comparatively easier, with a supporting effect of action-relatedness in the derivation of deverbal forms. This replicates and strengthens the finding that action-relatedness *per se* is not detrimental in PD, and may even act as a facilitative cue.

The more revealing pattern emerged when morphological complexity was manipulated while holding semantics as constant as possible. When participants had to produce morphologically complex event nominals such as *variazione* "variation", their performance diverged from that observed on the corresponding simplex or zero-derived event nouns, such as *cambio* "change". Healthy controls performed near ceiling across all morphological types. Individuals with PD, instead showed a graded impairment: accuracy was relatively preserved for simple nouns (e.g., *festa* "party"), modestly reduced for zero-derived nouns (e.g., *rilascio* "release"), and selectively impaired for complex event nominals (e.g., *evoluzione* “evolution”). In other words, the more the task required applying productive, rule-based suffixation processes that inherit and project the verbal event structure into a nominal template, the more vulnerable the PD group became.

This graded pattern is difficult to reconcile with a purely conceptual/semantic account. If the deficits were primarily rooted in building or accessing event-semantics representations, both complex nominals and their simple, synonymous counterparts should have been similarly affected. The fact that meaning-wise equivalent forms diverged as a function of morphological complexity, instead, points to a computation/storage distinction. Simple event nouns can be thought of as primarily stored entries, zero-derived forms require some limited derivational operation, and complex event nominals (formed with highly productive suffixed such as *-mento*, *-zione*, *tura*) demand rule-based computation over verbal roots. The observed impairment of rule-based forms seems to be graded according to the different degrees of morphological productivity of the retrieved forms (cf. Yang, 2016). The observation that PD performance deteriorates precisely along this storage-computation axis resonates with dual-mechanism accounts of morphology (Ullman’s 1997, 2016) and with the known reliance of rule-based morphological processes on fronto-striatal circuits, which are compromised in PD. Within this framework, the difficulty in PD is not in the concepts: it is in dynamically computing the right form when it is structurally complex and tightly bound to event-structure encoding.

In addition, Study 2 also compared verb base retrieval with the retrieval of the correspondent deverbal nominal. The results are only partially in line with those obtained by Silveri et al. (2018) and Di Tella et al. (2018), in which the base retrieval was a simpler condition. Our findings revealed that, in line with Study 1, the interplay between conceptual and morphosyntactic features is highly relevant. When high action-relatedness was embedded in deverbal nominals, it did not exacerbate the deficit, but it attenuated it, partially compensating for the cost of morphological complexity. Conversely, low-motion deverbal forms, lacking the action-relatedness conceptual support, were especially fragile. This convergence suggests that the same interface is under pressure in both studies: PD participants struggle not with either conceptual content of linguistic form *per se*, but with the process that has to align the two.

Study 3 moved beyond the language system and probed a domain-general mechanism, implicit statistical learning, implemented though an artificial grammar (Fibonacci L-system) and measured simultaneously at the level of motor responses and of anticipatory oculomotor behaviour. At first sight, the results might seem to diverge from the language findings. In fact, behaviourally individuals with PD were highly accurate, improved over blocks, and did not differ from controls in reaction times on correct trials. If implicit learning were to be evaluated only through motor performance, one might conclude that PD participants learned the structure of the sequence to a broadly similar extent as their matched counterparts.

However, the eye-tracking data tell a different part of the story. While healthy controls gradually developed robust anticipatory gaze patterns at the deterministic points of the Fibonacci grammar, increasingly fixating the correct area of interest during the preview window (before stimulus appeared), the PD group did not. Their predictive accuracy remained close to chance and largely flat across blocks, even in those positions where the upcoming stimulus was fully determined by the preceding context. In other words, exposure to the same structured sequence led neurotypical participants to internalise the rules in such a way that they could predict future stimuli, whereas individuals with PD largely remained in a reactive mood, responding accurately once the stimulus appeared but failing to convert this into a proactive, predictive strategy.

This dissociation between overall intact or mildly affected motor execution and impoverished predictive processing neatly echoes the linguistic findings. In all three studies, the basic capacity to react to presented input, naming a picture appearing on the screen, producing a stored simple noun, pressing the correct button once the stimulus has appeared, remains relatively spared. The fragility manifests itself when the system is required to project upward, for example when inferring a hidden causal structure behind an artefact, computing a derived nominal that inherits event structure, or shifting from reacting to stimuli to anticipating them on the basis of extracted regularities. That is precisely what I refer to as a “system-to-system” deficit: a difficulty in transmitting and transforming information between levels of representation, rather than in encoding that information at a single level.

In this sense, Study 3 does not stand apart from the language studies, but harmonises with them. It shows that even in a non-linguistic domain, where stimuli are rendered maximally abstract and devoid of semantic content, PD affects the ability to build predictive internal models from sequential input, especially at points of maximal determinism. And crucially, it does so in a way that cannot be reduced to motor slowness or inaccuracy, because motor behaviour alone would have led to a much more optimistic diagnosis of preserved implicit learning.

9.2 Summary and Conclusions

Taken together, the findings presented in this dissertation paint a coherent and theoretically informative picture of cognition in PD. In the three experimental studies, encompassing lexical access, derivational morphology, and implicit statistical learning, a consistent pattern emerged: individuals with PD do not show a breakdown of conceptual knowledge nor of action-related semantics, nor do they exhibit a categorical deficit restricted to verbs, nouns, or to a given level of the linguistic system. Instead, the core vulnerability lies in the transmission of information across levels of representation, that is, in the moment where conceptual structure must be mapped onto morphosyntactic forms, or where sequential regularities must be transferred from reactive motor responses to higher-level predictive anticipatory behaviour. The deficit is therefore best characterised as a system-to-system impairment, not as an impairment of the individual systems themselves.

This interpretation allows us to reconcile several initially contradictory findings in the existing literature. Paradigms that have found action-verb impairments often rely on tasks (and stimuli) that implicitly demand interface-level operations, for instance, embedding agentivity into morphosyntactic templates or integrating covert causation into lexical retrieval. The resulting apparent dissociations do not hold if the interface-level demands of these tasks are made explicit. Crucially, in our data, high action-relatedness consistently facilitated processing in PD, thus underscoring that the conceptual substrate is preserved and can even facilitate linguistic computation when the system is taxed. What turned out to be vulnerable is not the concepts involving actions, but the linguistic instantiation of action features in structurally complex environments.

The results of Study 3 bring this interpretation beyond the language domain. PD participants demonstrated intact or near-intact reactive motor learning, yet failed to convert that learning into predictive gaze behaviour, even under maximally deterministic conditions. The parallel with the linguistic studies is striking: what is spared is the ability to react to input, while what is compromised is the ability to use internalised (motor-based) structure to project to another system. The cross-domain convergence in naming, morphology and also in implicit learning suggests a shared computational bottleneck.

Some additional analyses, correlational work linking linguistic performance to implicit learning, and machine-learning classification using language and learning-based predictors, were intentionally kept separate and are included in full in Appendix 4. Both sets of analyses should be understood as valuable exploratory steps, as they offer preliminary insights that can pave the way for future work, which will require larger samples of participants and *ad hoc* designs. In more detail, the correlational results hinted at a distinct relationship between language and domain-general implicit learning capacities in PD compared to HCM (Appendix 4.1). The machine learning models, especially the Random Forest, provided a proof of concept that patterns of linguistic and implicit learning performance carry essential discriminative information when distinguishing between healthy (HCM) and pathological (PD) groups (Appendix 4.2). However, these results must be interpreted cautiously due to the sample size. Taken together, such exploratory analyses open promising avenues but are not yet meant to anchor strong theoretical claims at this initial stage. In the future, additional studies, ideally also longitudinal, are required to investigate further whether the identified interface-level processes could serve as early cognitive markers of PD.

Viewed as a whole, the present work advances a conceptual shift in how language and learning should be studied in PD. Rather than searching for isolated deficits in the domains of action semantics, verb processing, or sequence learning, we should focus on the operations that coordinate multiple cognitive systems, foregrounding the dynamic aspects of cognition: the processes that integrate conceptual features into linguistic form, that build morphological structure, and that transform sequential input into predictive models of future input. These are precisely the computations most dependent in the fronto-striatal circuitry affected in PD.

Finally, this dissertation highlights a broader methodological point. By combining detailed linguistic analysis with a principled artificial-grammar paradigm, it becomes possible to reveal subtle yet systematic patterns. In particular, predictive eye movements, fine-grained morphological processes, and the decomposition of conceptual-linguistic dimensions can unmask vulnerabilities that are otherwise masked by potential compensatory strategies. Future interdisciplinary research may contribute not only to the theoretical understanding of PD but also to the development of sensitive cognitive markers for diagnosis, monitoring, and personalised clinical intervention.

In conclusion, the evidence presented here argues for a unified, interface-based interpretation of linguistic and learning deficits in PD. This condition does not appear to affect conceptual representation or implicit learning capacities across the board, but rather has a more subtle effect that disrupts the bridges between systems, therefore weakening the ability to translate conceptual knowledge into linguistic form, or learned motor regularities into predictive behaviour. It is precisely at these junctions that PD produces its most consistent signature.

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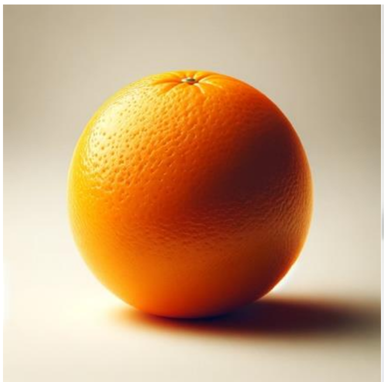
Appendixes

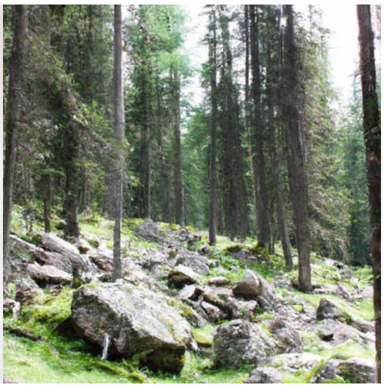
Appendix 1: Supplementary Materials for Study 1

Appendix 1.1: Training items for Nouns

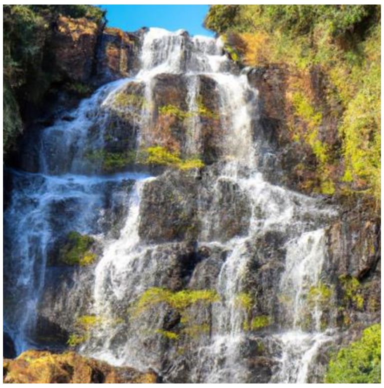
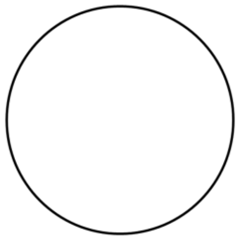
Appendix 1.2: Experimental items for Nouns















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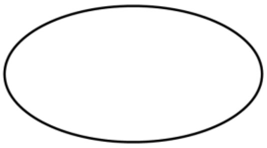
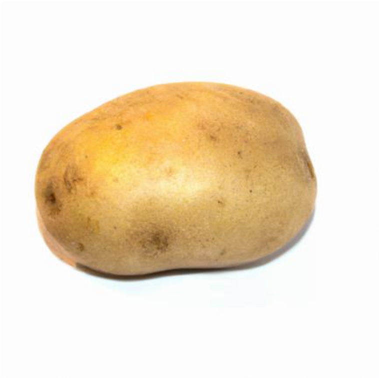
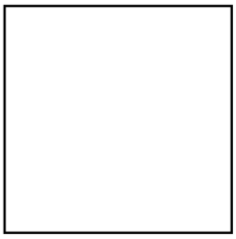
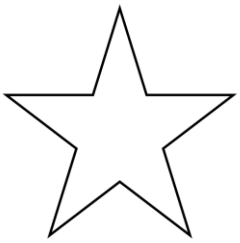
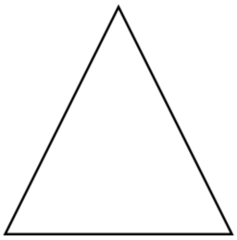










Appendix 1.3: Training items for Verbs

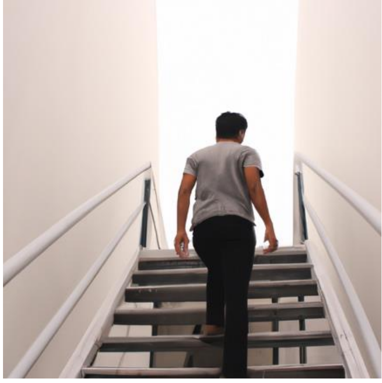
Appendix 1.4: Experimental items for Verbs

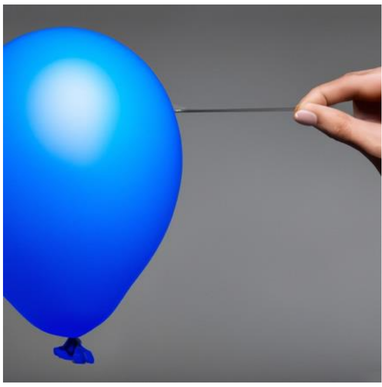








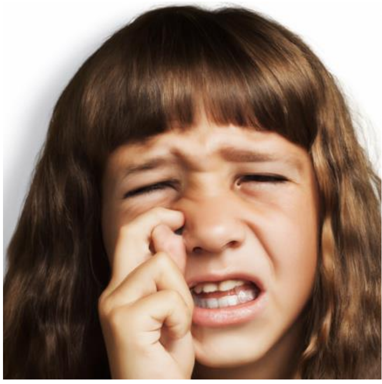








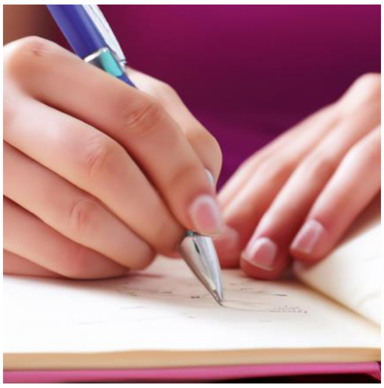









Appendix 2: Supplementary Materials for Study 2

Appendix 2.1: High-motion verbs vs. high-motion deverbal nominals

No.	Item		GC	Frequency itTenTen20	Relative Frequency itTenTen20	Length
1	Rompere	To break	V	567619	39,10685	7
2	Rottura	Breaking	N	303518	20,91127	7
3	Estrarre	To extract	V	337271	23,23673	8
4	Estrazione	Extraction	N	244086	16,81662	10
5	Aprire	To open	V	4232875	291,62944	6
6	Apertura	Opening	N	1444948	99,55158	8
7	Collegare	To connect	V	1319862	90,93361	9
8	Collegamento	Connection	N	813341	56,03619	12
9	Creare	To create	V	5250096	361,71221	6
10	Creazione	Creation	N	1096377	75,53632	9
11	Distruggere	To destroy	V	730474	50,32696	11
12	Distruzione	Destruction	N	314143	21,64329	11
13	Superare	To overtake	V	1963622	135,2863	8
14	Superamento	Overtaking	N	223327	15,3864	11
15	Sollevare	To lift	V	471807	32,50576	9
16	Sollevamento	Lifting	N	77077	5,31032	12
17	Ruotare	To rotate	V	202808	13,97272	7
18	Rotazione	Rotation	N	215065	14,81718	9
19	Inclinare	To tilt	V	98802	6,80709	9
20	Inclinazione	Tilt	N	110127	7,58734	12
21	Comprimere	To compress	V	129680	8,93447	10
22	Compressione	Compression	N	121576	8,37614	12
23	Rimuovere	To remove	V	620268	42,73417	9
24	Rimozione	Removal	N	265833	18,31491	9
25	Spostare	To move	V	1018970	70,20327	8
26	Spostamento	Movement	N	377343	25,99754	11
27	Scrivere	To write	V	6501031	447,89701	8
28	Scrittura	Writing	N	684610	47,1671	9

Appendix 2.2: Low-motion verbs vs. low-motion deverbal nominals

No.	Item		GC	Frequency itTenTen20	Relative Frequency itTenTen20	Length	Type
1	Comunicare	To communicate	V	1.323.750	91,20148	10	low motion
2	Comunicazione	Communication	N	2.235.065	153,98772	13	low motion
3	Descrivere	To describe	V	1.411.378	97,23873	10	low motion
4	Descrizione	Description	N	1.083.617	74,65721	11	low motion
5	Leggere	To read	V	5.210.816	359,00596	7	low motion
6	Lettura	Reading	N	1.546.445	106,54434	7	low motion
7	Spiegare	To explain	V	3.094.326	213,18762	8	low motion
8	Spiegazione	Explanation	N	453.575	31,24964	11	low motion
9	Osservare	To observe	V	1.588.378	109,43337	9	low motion
10	Osservazione	Observation	N	656.821	45,25254	12	low motion
11	Discutere	To discuss	V	698.598	48,13082	9	low motion
12	Discussione	Discussion	N	1.260.590	86,84999	11	low motion
13	Promuovere	To promote	V	1.567.929	108,02451	10	low motion
14	Promozione	Promotion	N	1.110.274	76,49377	10	low motion
15	Divertire	To amuse	V	593.379	40,88162	9	Psych
16	Divertimento	Amusement	N	476,208	32,80897	11	Psych
17	Intrattenere	To entertain	V	143.337	9,87539	12	Psych
18	Intrattenimento	Entertainment	N	214.027	14,74567	15	Psych
19	Preoccupare	To worry	V	747.514	51,50095	11	Psych
20	Preoccupazione	Worry	N	448.863	30,925	14	Psych
21	Deludere	To disappoint	V	209.829	14,45644	8	Psych
22	Delusione	Disappointment	N	185.159	12,75677	9	Psych
23	Irritare	To irritate	V	82.154	5,66011	8	Psych
24	Irritazione	Irritation	N	75.241	5,18383	11	Psych
25	Confondere	To confuse	V	364.827	25,13523	10	Psych
26	Confusione	Confusion	N	294.228	20,27122	10	Psych
27	Indignare	To make indignant	V	58.078	4,00136	9	Psych
28	Indignazione	Indignation	N	58.466	4,02809	11	Psych

Appendix 2.3: Elicitation sentences High-motion verbs vs. high-motion deverbal nominals

1. La rottura del vaso è stata intenzionale. Martina ha dato una spinta per farlo… ROMPERE
2. Il bambino rischia di rompere la finestra con la palla. Il bambino potrebbe causare la sua improvvisa… ROTTURA
3. L'estrazione del dente è durata dieci minuti. Il dentista ha usato una pinza per poterlo… ESTRARRE
4. Il minatore deve estrarre il diamante dalla roccia. Il minatore deve occuparsi della sua difficoltosa… ESTRAZIONE
5. L'apertura del negozio è avvenuta alle 9. Il commesso ha alzato la saracinesca per poterlo… APRIRE
6. Elena vuole aprire la porta della cantina. Elena vuole causare la sua completa… APERTURA
7. Il collegamento dei tubi è stato complesso. L'idraulico ha usato degli strumenti per poterli… COLLEGARE
8. L'elettricista deve collegare bene il cavo della corrente. L'elettricista deve occuparsi del suo corretto… COLLEGAMENTO
9. La creazione del foro è stata difficoltosa. Pietro ha usato un trapano per poterlo… CREARE
10. Francesca vuole creare un castello con le carte. Francesca vuole riuscire nella sua delicata… CREAZIONE
11. La distruzione del muro è durata parecchi giorni. Paolo ha usato un piccone per poterlo… DISTRUGGERE
12. Il vandalo vuole distruggere la statua con una mazza. Il vandalo vuole causare la sua completa… DISTRUZIONE
13. Il superamento del corridore ha richiesto un grande sforzo. L'atleta ha corso molto velocemente per poterlo… SUPERARE
14. Giulia vuole superare lo sfidante nella corsa. Giulia vuole riuscire nel suo rapido… SUPERAMENTO
15. Il sollevamento del peso ha richiesto molta forza. Roberta ha fatto molta fatica per poterlo… SOLLEVARE
16. Andrea vuole sollevare il divano da terra. Andrea vuole riuscire nel suo faticoso… SOLLEVAMENTO
17. La rotazione del bullone ha richiesto molta manualità. Federico ha usato una chiave inglese per poterlo… RUOTARE
18. Gianni vuole ruotare un poco la manopola del forno. Gianni vuole causare la sua parziale… ROTAZIONE
19. L'inclinazione della ciotola ha richiesto molta attenzione. Elisa ha sollevato la ciotola per poterla… INCLINARE

20. Maria vuole inclinare un po’ la lampada sul comodino. Maria vuole causare la sua parziale… INCLINAZIONE
21. La compressione della bottiglia è stata faticosa. Sara ha usato molta forza per poterla… COMPRIMERE
22. Luca vuole comprimere la lattina di birra. Luca vuole causare la sua rapida... COMPRESSIONE
23. La rimozione delle piastrelle è durata alcune ore. Francesco ha usato degli attrezzi per poterle… RIMUOVERE
24. Matteo deve rimuovere gli ostacoli dal percorso. Matteo deve occuparsi della loro completa… RIMOZIONE
25. Lo spostamento del tavolo ha richiesto molta energia. Giacomo ha chiesto aiuto per poterlo… SPOSTARE
26. Marco deve spostare i mobili di casa. Marco deve occuparsi del loro impegnativo... SPOSTAMENTO
27. La scrittura della lettera ha richiesto alcune ore. Alice ha usato molti fogli per poterla… SCRIVERE
28. Angelica deve scrivere un articolo al computer. Angelica deve occuparsi della sua accurata… SCRITTURA

Appendix 2.4: Elicitation sentences Low-motion verbs vs. low-motion deverbal nominals

1. La comunicazione delle nuove regole ha richiesto molta attenzione. Il direttore ha usato un megafono per poterle… COMUNICARE
2. Marco deve comunicare la notizia ai colleghi. Marco deve occuparsi della sua... COMUNICAZIONE
3. La descrizione dell’incidente è stata molto dettagliata. Il testimone ha fornito numerose informazioni per poterlo… DESCRIVERE
4. Alessio deve descrivere l’immagine. Alessio deve occuparsi della sua… DESCRIZIONE
5. La lettura del romanzo ha richiesto tre mesi. A Nicola è servito molto tempo per poterlo… LEGGERE
6. Tamara vuole leggere le istruzioni della lavatrice. Tamara vuole dedicarsi alla loro… LETTURA
7. La spiegazione della poesia ha permesso di capirla meglio. Il poeta ha usato parole semplici per poterla… SPIEGARE
8. L’insegnante vuole spiegare un nuovo argomento. L’insegnante vuole occuparsi della sua… SPIEGAZIONE

9. L’osservazione degli animali ha richiesto molta pazienza. Davide ha aspettato diverse ore per poterli… OSSERVARE
10. Serena vuole osservare le stelle dalla finestra. Serena usa un telescopio per la loro… OSSERVAZIONE
11. La discussione della nuova legge è durata tutta la mattina. Il parlamentare si è preparato molto per poterla… DISCUTERE
12. Renzo deve discutere la tesi. Renzo vuole prepararsi per la sua… DISCUSSIONE
13. La promozione di Lara è stata improvvisa. Il capo ha deciso in pochi giorni di volerla… PROMUOVERE
14. Carlo vuole promuovere il suo dipendente. Carlo vuole sostenere la sua… PROMOZIONE
15. Il divertimento di Lucia era prevedibile. La mamma l’ha portata alle giostre per farla… DIVERTIRE
16. Tommaso vuole divertire il collega con le sue barzellette. Tommaso vuole causare il suo… DIVERTIMENTO
17. L’intrattenimento degli spettatori è stato faticoso. Il conduttore ha fatto molte battute per poterli… INTRATTENERE
18. Marta vuole intrattenere gli ospiti con i balli di gruppo. Marta vuole occuparsi del loro… INTRATTENIMENTO
19. La preoccupazione di Marianna è stata molto grande. Sua figlia si era allontanata per farla… PREOCCUPARE
20. Ugo rischia di preoccupare la moglie con il suo atteggiamento. Ugo rischia di causare la sua… PREOCCUPAZIONE
21. La delusione del maestro è stata grandissima. Lo scolaro birichino ha fatto di tutto per poterlo… DELUDERE
22. Piero teme di deludere il suo amico. Piero teme di causare la sua… DELUSIONE
23. L’irritazione di Gianni era giustificata. Il suo vicino ha combinato di tutto per farlo… IRRITARE
24. L’alunno vuole irritare l’insegnante parlando di continuo. L’alunno vuole causare la sua… IRRITAZIONE
25. La confusione di Alice era evidente. Il mago ha usato un trucco per farla… CONFONDERE
26. Gaia vuole confondere l’avversario negli scacchi. Gaia vuole causare la sua… CONFUSIONE
27. L’indignazione di Matteo era molto forte. Il politico si è comportato così male da farlo… INDIGNARE
28. Il sindaco potrebbe indignare i cittadini con le sue decisioni. Il sindaco potrebbe suscitare la loro… INDIGNAZIONE

Appendix 2.5: Complex event nominals vs. simple and zero-derived nouns denoting events

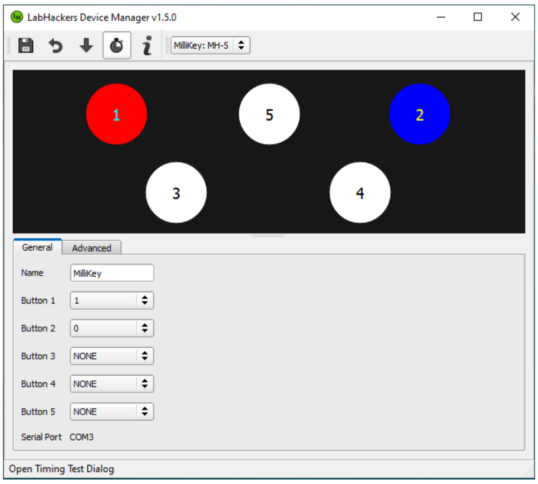
No	Item		GC	Frequency itTenTen20	Relative Frequency itTenTen20	Length	Type
1	celebrazione	celebration	N	343.778	23,68503	12	CEN
2	festa	party	N	1.828.093	125,94885	5	simple
3	combattimento	fighting	N	288.746	19,89353	13	CEN
4	guerra	war	N	3.127.925	215,50247	6	simple
5	complicazione	complication	N	104.276	7,18423	13	CEN
6	problema	problem	N	6.807.677	469,02378	8	simple
7	valutazione	evaluation	N	1.651.170	113,75951	11	CEN
8	esame	exam	N	1.685.072	116,09523	5	simple
9	competizione	competition	N	451.811	31,12811	12	CEN
10	gara	race	N	2.294.502	158,08271	4	simple
11	rappresentazione	representation	N	494.041	34,0376	16	CEN
12	scena	scene	N	1.775.064	122,29535	5	simple
13	ammaccatura	bump	N	8.736	0,60188	11	CEN
14	danno	damage	N	1.807.512	124,5309	5	simple
15	variazione	variation	N	547.589	37,72686	10	CEN
16	cambio	change	N	1.145.961	78,95248	6	zero
17	liberazione	liberation	N	1.015.699	69,97791	11	CEN
18	rilascio	release	N	7.741.199	533,34	4	zero
19	evoluzione	evolution	N	892.680	61,50235	11	CEN
20	sviluppo	development	N	1.456.990	100,38123	6	zero
21	esplosione	explosion	N	232.666	16,02983	10	CEN
22	scoppio	burst	N	108.663	7,48648	7	zero
23	violazione	violation	N	570.186	39,28371	10	CEN
24	abuso	abuse	N	827.149	56,98751	5	zero
25	negazione	negation	N	83.945	5,7835	9	CEN
26	rifiuto	refusal	N	1.197.887	82,52999	7	zero
27	aggressione	aggression	N	182.307	12,56028	11	CEN
28	attacco	attack	N	1.305.021	89,91112	7	zero

Appendix 2.6: Elicitation sentences complex event nominals vs. simple and zero-derived nouns denoting events

1. Gli sposi sono pronti a celebrare il loro matrimonio. Gli sposi daranno presto il via alla festosa… CELEBRAZIONE
2. Luca vuole festeggiare il suo compleanno sulla spiaggia. Luca ha organizzato una grande… FESTA
3. Gli eroi sono riusciti a combattere senza sosta. Gli eroi si sono impegnati in un estenuante… COMBATTIMENTO
4. I militari erano stanchi di guerreggiare. I militari avevano visto la brutalità della… GUERRA
5. Lo scrittore vuole complicare la trama del romanzo. Lo scrittore intende inserire un’ulteriore… COMPLICAZIONE
6. Franco tende a problematizzare ogni situazione. Franco è alla costante ricerca di un… PROBLEMA
7. Giacomo vuole valutare bene la proposta di lavoro. Giacomo vuole sottoporla a un’attenta… VALUTAZIONE
8. Il chimico deve esaminare il nuovo composto. Il chimico deve sottoporlo a un accurato… ESAME
9. Carlo deve competere contro gli atleti migliori del mondo. Carlo si è allenato molto per la durissima… COMPETIZIONE
10. Sofia ha deciso di gareggiare nella maratona di sabato. Sofia si è preparata per questa lunghissima… GARA
11. Il regista vuole rappresentare una realtà contraddittoria. Il regista vuole creare una suggestiva… RAPPRESENTAZIONE
12. Alessandra è riuscita a sceneggiare un racconto per bambini. Gli attori hanno già provato la prima… SCENA
13. Flavio rischia di ammaccare l’auto parcheggiando di fretta. Flavio rischia di creare una grossa… AMMACCATURA
14. Rita rischia di danneggiare il libro con l’acqua. Rita rischia di provocare un grosso… DANNO
15. Emanuela deve variare il programma del giorno. Emanuela deve apportare una… VARIAZIONE
16. Gianmarco vuole cambiare la camicia troppo stretta. Gianmarco vuole effettuare un… CAMBIO
17. I militari vogliono liberare gli ostaggi. Al momento giusto i militari procederanno alla loro… LIBERAZIONE
18. Il rapitore intende finalmente rilasciare i prigionieri. Nel pomeriggio il rapitore procederà al loro… RILASCIO

19. Grazie al suo intelletto l’uomo si è potuto evolvere. L’uomo è riuscito nella sua… EVOLUZIONE
20. Ugo vuole sviluppare le proprie competenze. Ugo si impegna costantemente nel proprio… SVILUPPO
21. L’addetto ha fatto esplodere i materiali chimici. L’addetto ha provocato una violenta… ESPLOSIONE
22. Adriano ha fatto scoppiare un petardo. Adriano ha generato un fragoroso… SCOPPIO
23. Il criminale è riuscito a violare la legge. Il criminale ha commesso una grave… VIOLAZIONE
24. Francesco ha voluto abusare del proprio potere. Francesco ha commesso un inaccettabile… ABUSO
25. Fabio tende a negare la sua disponibilità. Fabio risponde spesso con una categorica… NEGAZIONE
26. Guido ha dovuto rifiutare la proposta. Guido ha espresso a malincuore il suo... RIFIUTO
27. Il manifestante ha tentato di aggredire un poliziotto. Il manifestante ha dovuto rispondere per la tentata… AGGRESSIONE
28. Il terrorista ha voluto attaccare la città. Il terrorista ha scagliato su di essa un devastante… ATTACCO

Appendix 3: Supplementary Materials for Study 3



Name MilliKey
Button 1 1
Button 2 0
Button 3 NONE
Button 4 NONE
Button 5 NONE
Serial Port COM3

Figure 34. Response Box Configuration

Appendix 4: Other Supplementary Materials

Appendix 4.1: Domain-General and Domain-Specific: Correlational Insights

Domain-general skills, such as implicit statistical learning, are believed to interact with domain-specific skills, such as language, although the nature of this interaction is not always clear. Auditory-linguistic statistical learning appears to play a foundational role in language acquisition (Isbilen & Christiansen, 2022) and processing, yet demonstrating this link experimentally is far from being a trivial endeavour. This challenge stems from the complexity of statistical learning as a theoretical construct (Siegelman, 2020) and from individual differences (Bogaerts, Crepaldi, Zhou, Siegelman et al., 2024). Other studies have examined how these domain-general abilities are related to language deficits, for example in the context of specific language impairment and dyslexia (Bogaerts et al., 2021).

This section aims to explore the relationship between language and implicit learning through correlational evidence. Specifically, correlations were computed between outcome measures in naming and implicit learning tasks, and group-specific differences were investigated.

Metrics Selection

A first batch of twelve indexes were calculated from the linguistic tasks to serve as proxies for linguistic performance. Some more specific indexes included the involvement of action-relatedness (here considered as a binary categorical variable):

reaction times in verb naming	(rt_verb_naming_all)
accuracy in verb naming	(acc_verb_naming_all)
reaction times in noun naming	(rt_noun_naming_all)
accuracy in noun naming	(acc_noun_naming_all)
reaction times in naming verbs with high action-relatedness	(rt_verb_naming_highmotion)
reaction times in naming verbs with low action-relatedness	(rt_verb_naming_lowmotion)
accuracy in naming verbs with high action-relatedness	(acc_verb_naming_highmotion)
accuracy in naming verbs with low action-relatedness	(acc_verb_naming_lowmotion)
reaction times in naming nouns with high action-relatedness	(rt_noun_naming_highmotion)
reaction times in naming nouns with low action-relatedness	(rt_noun_naming_lowmotion)
accuracy in naming nouns with high action-relatedness	(acc_noun_naming_highmotion)
accuracy in naming nouns with low action-relatedness	(acc_noun_naming_lowmotion)

A second batch of fourteen indexes were calculated from the linguistic task to analyse correlations with noun naming performance:

average reaction times in noun naming for “shapes”	(rt_noun_naming_shapes)
average reaction times in noun naming for “naturals”	(rt_noun_naming_naturals)
average reaction times in noun naming for “tools”	(rt_noun_naming_tools)
average reaction times in noun naming for “ready-to-eat food”	(rt_noun_naming_ready)
average reaction times in noun naming for “food requiring hand action”	(rt_noun_naming_handact)
average reaction times in noun naming for “food requiring tool actions”	(rt_noun_naming_toolact)
average reaction times in noun naming for “artefacts”	(rt_noun_naming_artefacts)
average accuracy in noun naming for “shapes”	(acc_noun_naming_shapes)
average accuracy in noun naming for “naturals”	(acc_noun_naming_naturals)
average accuracy in noun naming for “tools”	(acc_noun_naming_tools)
average accuracy in noun naming for “ready-to-eat food”	(acc_noun_naming_ready)
average accuracy in noun naming for “food requiring hand action”	(acc_noun_naming_handact)
average accuracy in noun naming for “food requiring tool actions”	(acc_noun_naming_toolact)
average accuracy in noun naming for “artefacts”	(acc_noun_naming_artefact)

A third and last batch of ten indexes were calculated from the linguistic task to analyse correlations with verb naming performance:

average reaction times in verb naming for “transitive accomplishment”	(rt_verb_naming_transitiveacc)
average reaction times in verb naming for “transitive achievement”	(rt_verb_naming_transitiveach)
average reaction times in verb naming for “unaccusative”	(rt_verb_naming_unacc)
average reaction times in verb naming for “unergative”	(rt_verb_naming_unerg)
average reaction times in verb naming for “unergative internal”	(rt_verb_naming_unergint)
average accuracy in verb naming for “transitive accomplishment”	(acc_verb_naming_transitiveacc)
average accuracy in verb naming for “transitive achievement”	(acc_verb_naming_transitiveach)
average accuracy in verb naming for “unaccusative”	(acc_verb_naming_unacc)
average accuracy in verb naming for “unergative”	(acc_verb_naming_unerg)
average accuracy in verb naming for “unergative internal”	(acc_verb_naming_unergint)

Eleven indexes were calculated from the Fib-grammar-based task to serve as proxies for domain-general implicit learning skills. The following were based on the behavioural button-press responses:

average accuracy in all Fib points	(acc_fiball)
average reaction times in all Fib points	(rt_fiball_blockall)
delta reaction times in Fib point [0**1**] at Block 1 minus Block 6	(rt_fib01_blockdelta1-6)
delta reaction times in Fib point [11**0**] at Block 1 minus Block 6	(rt_fib110_blockdelta1-6)

delta reaction times in Fib point [01**1**] at Block 1 minus Block 6	(rt_fib011_blockdelta1-6)
delta reaction times in Fib point [01**0**] at Block 1 minus Block 6	(rt_fib010_blockdelta1-6)

The following were instead derived from eye-tracking oculomotor anticipations:

average prediction accuracy in Fib point [0**1**]	(pred_acc_fib01_blockall)
average prediction accuracy in Fib point [11**0**]	(pred_acc_fib110_blockall)
average prediction accuracy in Fib point [01**1**]	(pred_acc_fib011_blockall)
average prediction accuracy in Fib point [01**0**]	(pred_acc_fib010_blockall)
average prediction accuracy in all points	(pred_acc_fiball_blockall)

Statistical Analysis

Correlations between General Linguistic Measures and Implicit Learning Measures

Correlational analyses were performed to examine the relationship between linguistic and implicit learning measures within each participant group. Pearson's correlations were computed between each linguistic predictor (12 variables) and each implicit learning predictor (11 variables), yielding a total of 132 pairwise correlations per group. Each correlation was tested for statistical significance, and *p*-values were adjusted for multiple comparisons using the False Discovery Rate (FDR; Benjamini & Hochberg, 1995). Separate correlation matrices were generated for each group, with linguistic measures represented as rows and implicit learning measures as columns. For each intersection cell, the correlation coefficient (*r*) is reported in the following figures, and correlations surviving FDR are marked with an asterisk (*).

Moreover, group differences in correlation strength were assessed by comparison Fisher *r*-to-*z* transformed values between PD and HCM for the corresponding pairs of variables. This allowed us to identify whether the relation between specific linguistic and implicit learning measures differed significantly across groups.

Correlations between Noun Linguistic Measures and Implicit Learning Measures

With the exact same procedure, an additional correlational analysis was run to explore the correlations between linguistic measures on noun naming (14 variables), corresponding to accuracy and reaction times rates per each of the seven nominal categories contained in the naming dataset (cfr. Chapter 6, Study 1) and the implicit learning predictors identified above (11 variables).

Correlations between Verb Linguistic Measures and Implicit Learning Measures

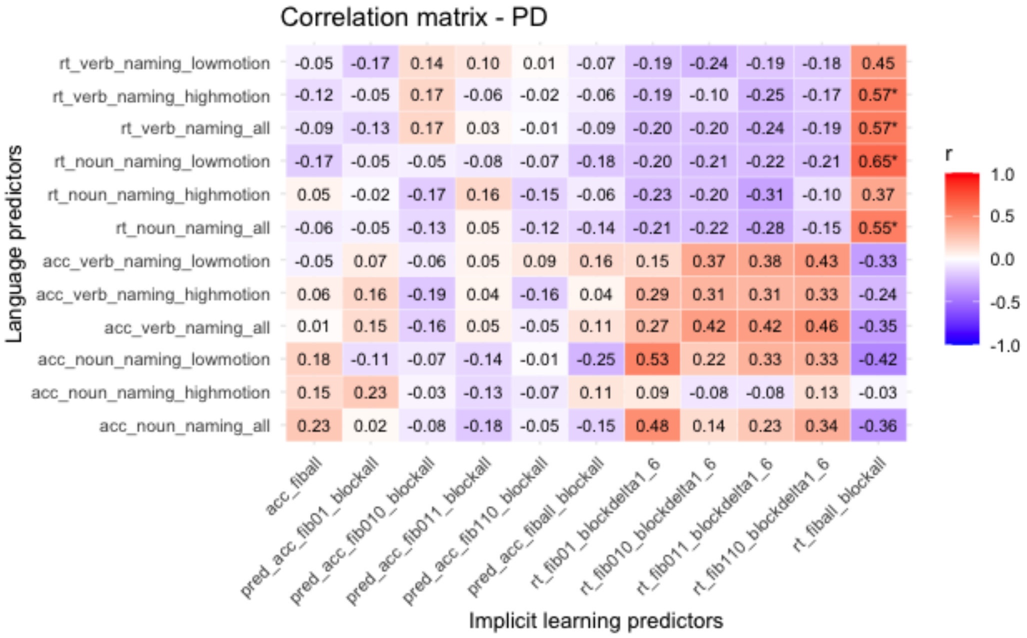
A final correlational analysis was run to explore the correlations between linguistic measures on verb naming (10 variables), corresponding to accuracy and reaction times rates per each of the five verbal categories contained in the naming dataset (cfr. Chapter 6, Study 1), and the implicit learning predictors identified above (11 variables).

Results: Correlational Evidence

Correlations between General Linguistic Measures and Implicit Learning Measures

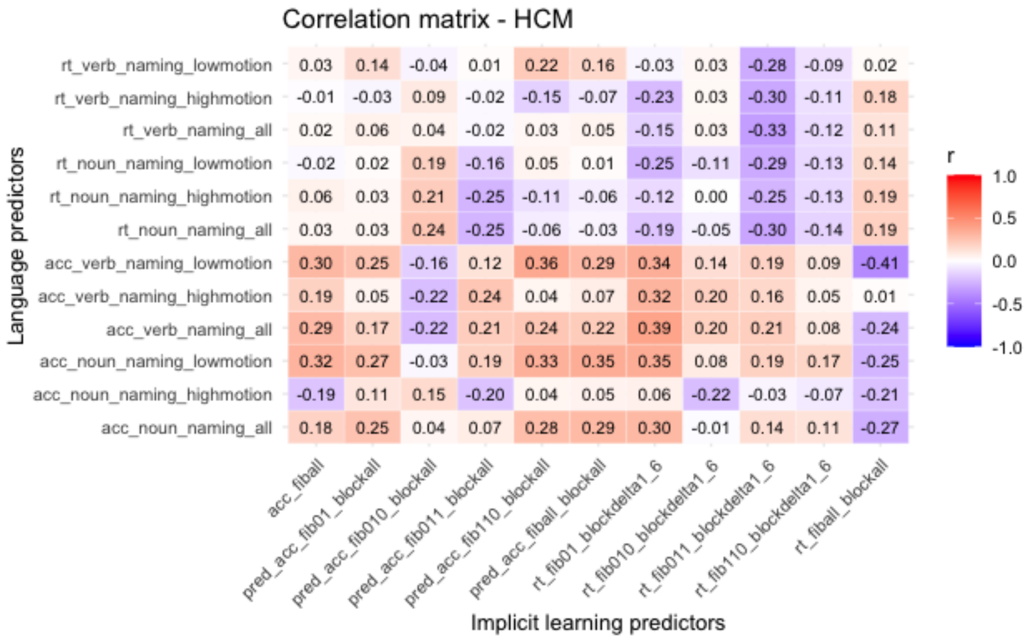
Across the 132 pairwise correlations, the pattern of associations differed between groups. In the PD group, four correlations survived FDR correction ($p < .05$, see correlation matrix in Figure 35). All involved reaction times in naming task and in the implicit learning index rt_fiball_blockall, representing mean reaction times across all the points of the Fib grammar. More specifically, longer latencies in the implicit learning task were significantly associated with longer naming reaction times for all verbs, all nouns, nouns with low-action relatedness, verbs with high action-relatedness. No significant correlation was observed for accuracy-based measures in PD, nor for any variables in the HCM group after FDR correction (all $p > .05$, see correlation matrix in Figure 36).

Direct group comparisons were performed using Fisher *r*-to-*z* transformations. These revealed no statistically significant differences in correlation strength between PD and HCM, indicating that although these associations were present in the PD group only, between-group contrasts did not reach corrected significance.



	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_verb_naming_lowmotion	-0.05	-0.17	0.14	0.10	0.01	-0.07	-0.19	-0.24	-0.19	-0.18	0.45
rt_verb_naming_highmotion	-0.12	-0.05	0.17	-0.06	-0.02	-0.06	-0.19	-0.10	-0.25	-0.17	0.57*
rt_verb_naming_all	-0.09	-0.13	0.17	0.03	-0.01	-0.09	-0.20	-0.20	-0.24	-0.19	0.57*
rt_noun_naming_lowmotion	-0.17	-0.05	-0.05	-0.08	-0.07	-0.18	-0.20	-0.21	-0.22	-0.21	0.65*
rt_noun_naming_highmotion	0.05	-0.02	-0.17	0.16	-0.15	-0.06	-0.23	-0.20	-0.31	-0.10	0.37
rt_noun_naming_all	-0.06	-0.05	-0.13	0.05	-0.12	-0.14	-0.21	-0.22	-0.28	-0.15	0.55*
acc_verb_naming_lowmotion	-0.05	0.07	-0.06	0.05	0.09	0.16	0.15	0.37	0.38	0.43	-0.33
acc_verb_naming_highmotion	0.06	0.16	-0.19	0.04	-0.16	0.04	0.29	0.31	0.31	0.33	-0.24
acc_verb_naming_all	0.01	0.15	-0.16	0.05	-0.05	0.11	0.27	0.42	0.42	0.46	-0.35
acc_noun_naming_lowmotion	0.18	-0.11	-0.07	-0.14	-0.01	-0.25	0.53	0.22	0.33	0.33	-0.42
acc_noun_naming_highmotion	0.15	0.23	-0.03	-0.13	-0.07	0.11	0.09	-0.08	-0.08	0.13	-0.03
acc_noun_naming_all	0.23	0.02	-0.08	-0.18	-0.05	-0.15	0.48	0.14	0.23	0.34	-0.36

Figure 35. Correlation Matrix between Linguistic and Implicit Learning Metrics in PD



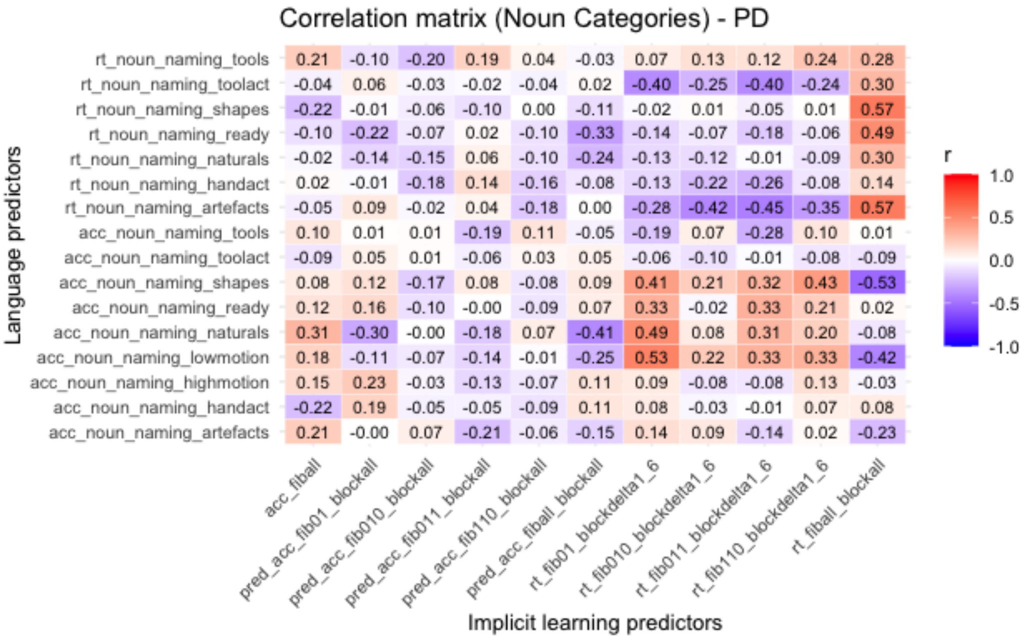
	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_verb_naming_lowmotion	0.03	0.14	-0.04	0.01	0.22	0.16	-0.03	0.03	-0.28	-0.09	0.02
rt_verb_naming_highmotion	-0.01	-0.03	0.09	-0.02	-0.15	-0.07	-0.23	0.03	-0.30	-0.11	0.18
rt_verb_naming_all	0.02	0.06	0.04	-0.02	0.03	0.05	-0.15	0.03	-0.33	-0.12	0.11
rt_noun_naming_lowmotion	-0.02	0.02	0.19	-0.16	0.05	0.01	-0.25	-0.11	-0.29	-0.13	0.14
rt_noun_naming_highmotion	0.06	0.03	0.21	-0.25	-0.11	-0.06	-0.12	0.00	-0.25	-0.13	0.19
rt_noun_naming_all	0.03	0.03	0.24	-0.25	-0.06	-0.03	-0.19	-0.05	-0.30	-0.14	0.19
acc_verb_naming_lowmotion	0.30	0.25	-0.16	0.12	0.36	0.29	0.34	0.14	0.19	0.09	-0.41
acc_verb_naming_highmotion	0.19	0.05	-0.22	0.24	0.04	0.07	0.32	0.20	0.16	0.05	0.01
acc_verb_naming_all	0.29	0.17	-0.22	0.21	0.24	0.22	0.39	0.20	0.21	0.08	-0.24
acc_noun_naming_lowmotion	0.32	0.27	-0.03	0.19	0.33	0.35	0.35	0.08	0.19	0.17	-0.25
acc_noun_naming_highmotion	-0.19	0.11	0.15	-0.20	0.04	0.05	0.06	-0.22	-0.03	-0.07	-0.21
acc_noun_naming_all	0.18	0.25	0.04	0.07	0.28	0.29	0.30	-0.01	0.14	0.11	-0.27

Figure 36. Correlation Matrix between Linguistic and Implicit Learning Metrics in HCM

Overall, the insights provided by the correlational analysis suggest that, in individuals with PD, slower implicit learning sequence processing is linked to slower lexical retrieval. In other words, reaction times when responding to visual stimuli on the screen via button-press correlate with the reaction times needed to retrieve the word corresponding to pictures depicting verbs and nouns. Rather than a shared processing mechanism, these reaction-time-based correlational results seem to capture a shared deficit in planning and initiation, that might be involved in both button-press and lexical selection, relying on the fronto-striatal network compromised in PD.

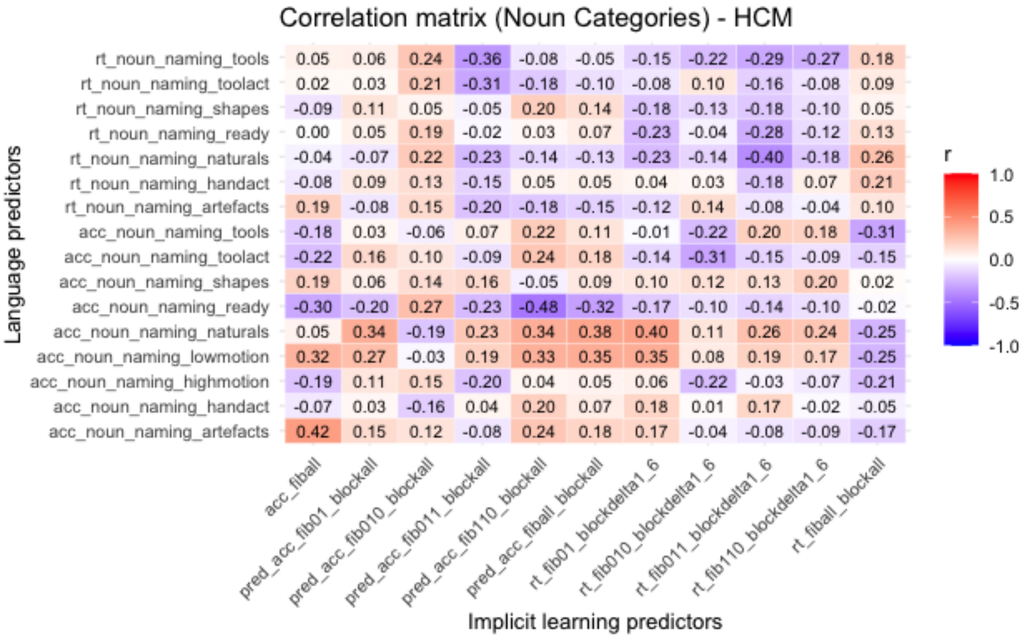
The absence of such a correlation in the healthy control group suggests that the association is primarily quantitative (in processing speed) rather than qualitative (in task success or learning outcome). This distinction highlights that the connection between implicit learning and language performance in PD may depend more on processing speed than on the integrity of representational learning *per se*. These associations might emerge as a byproduct of disease-related alterations in motor and cognitive control systems. The convergence of reaction times across linguistic and implicit learning tasks identified for the PD group only may reflect a domain-general slowing related to basal ganglia dysfunction that permeates the processing requirements of both tasks, affecting both implicit learning processing and lexical retrieval timing. This is consistent with frameworks that conceptualise the basal ganglia as a central hub for both motor and linguistic sequencing, mediating the predictive and timing aspects of cognition (Kotz & Schwartze, 2010; Ullman, 2016).

Correlations between Noun Linguistic Measures and Implicit Learning Measures



	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_noun_naming_tools	0.21	-0.10	-0.20	0.19	0.04	-0.03	0.07	0.13	0.12	0.24	0.28
rt_noun_naming_toolact	-0.04	0.06	-0.03	-0.02	-0.04	0.02	-0.40	-0.25	-0.40	-0.24	0.30
rt_noun_naming_shapes	-0.22	-0.01	-0.06	-0.10	0.00	-0.11	-0.02	0.01	-0.05	0.01	0.57
rt_noun_naming_ready	-0.10	-0.22	-0.07	0.02	-0.10	-0.33	-0.14	-0.07	-0.18	-0.06	0.49
rt_noun_naming_naturals	-0.02	-0.14	-0.15	0.06	-0.10	-0.24	-0.13	-0.12	-0.01	-0.09	0.30
rt_noun_naming_handact	0.02	-0.01	-0.18	0.14	-0.16	-0.08	-0.13	-0.22	-0.26	-0.08	0.14
rt_noun_naming_artefacts	-0.05	0.09	-0.02	0.04	-0.18	0.00	-0.28	-0.42	-0.45	-0.35	0.57
acc_noun_naming_tools	0.10	0.01	0.01	-0.19	0.11	-0.05	-0.19	0.07	-0.28	0.10	0.01
acc_noun_naming_toolact	-0.09	0.05	0.01	-0.06	0.03	0.05	-0.06	-0.10	-0.01	-0.08	-0.09
acc_noun_naming_shapes	0.08	0.12	-0.17	0.08	-0.08	0.09	0.41	0.21	0.32	0.43	-0.53
acc_noun_naming_ready	0.12	0.16	-0.10	-0.00	-0.09	0.07	0.33	-0.02	0.33	0.21	0.02
acc_noun_naming_naturals	0.31	-0.30	-0.00	-0.18	0.07	-0.41	0.49	0.08	0.31	0.20	-0.08
acc_noun_naming_lowmotion	0.18	-0.11	-0.07	-0.14	-0.01	-0.25	0.53	0.22	0.33	0.33	-0.42
acc_noun_naming_highmotion	0.15	0.23	-0.03	-0.13	-0.07	0.11	0.09	-0.08	-0.08	0.13	-0.03
acc_noun_naming_handact	-0.22	0.19	-0.05	-0.05	-0.09	0.11	0.08	-0.03	-0.01	0.07	0.08
acc_noun_naming_artefacts	0.21	-0.00	0.07	-0.21	-0.06	-0.15	0.14	0.09	-0.14	0.02	-0.23

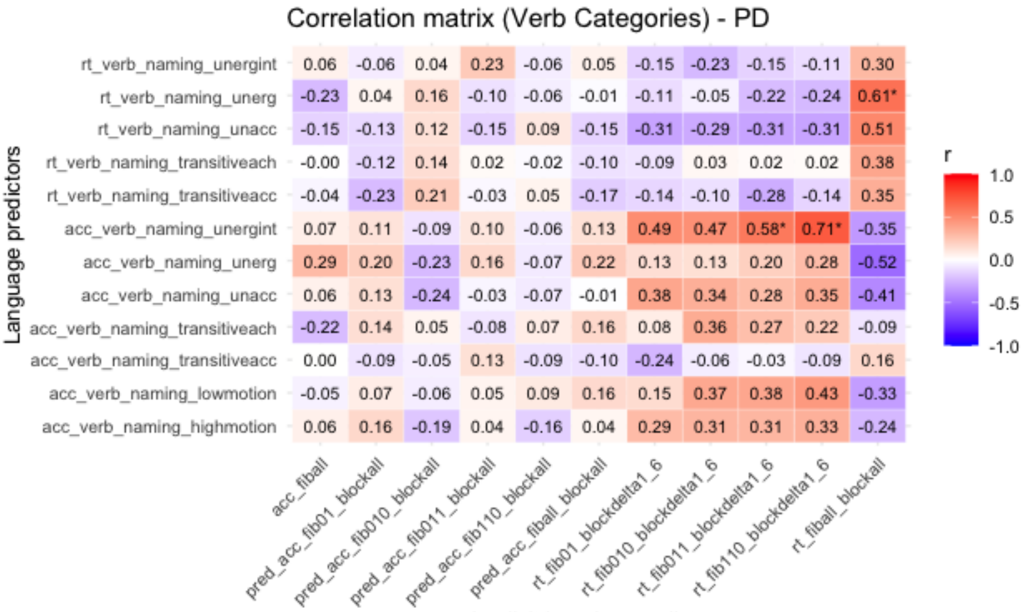
Figure 37. Correlation Matrix between Noun Linguistic Measures and Implicit Learning Metrics in PD



	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_noun_naming_tools	0.05	0.06	0.24	-0.36	-0.08	-0.05	-0.15	-0.22	-0.29	-0.27	0.18
rt_noun_naming_toolact	0.02	0.03	0.21	-0.31	-0.18	-0.10	-0.08	0.10	-0.16	-0.08	0.09
rt_noun_naming_shapes	-0.09	0.11	0.05	-0.05	0.20	0.14	-0.18	-0.13	-0.18	-0.10	0.05
rt_noun_naming_ready	0.00	0.05	0.19	-0.02	0.03	0.07	-0.23	-0.04	-0.28	-0.12	0.13
rt_noun_naming_naturals	-0.04	-0.07	0.22	-0.23	-0.14	-0.13	-0.23	-0.14	-0.40	-0.18	0.26
rt_noun_naming_handact	-0.08	0.09	0.13	-0.15	0.05	0.05	0.04	0.03	-0.18	0.07	0.21
rt_noun_naming_artefacts	0.19	-0.08	0.15	-0.20	-0.18	-0.15	-0.12	0.14	-0.08	-0.04	0.10
acc_noun_naming_tools	-0.18	0.03	-0.06	0.07	0.22	0.11	-0.01	-0.22	0.20	0.18	-0.31
acc_noun_naming_toolact	-0.22	0.16	0.10	-0.09	0.24	0.18	-0.14	-0.31	-0.15	-0.09	-0.15
acc_noun_naming_shapes	0.19	0.06	0.14	0.16	-0.05	0.09	0.10	0.12	0.13	0.20	0.02
acc_noun_naming_ready	-0.30	-0.20	0.27	-0.23	-0.48	-0.32	-0.17	-0.10	-0.14	-0.10	-0.02
acc_noun_naming_naturals	0.05	0.34	-0.19	0.23	0.34	0.38	0.40	0.11	0.26	0.24	-0.25
acc_noun_naming_lowmotion	0.32	0.27	-0.03	0.19	0.33	0.35	0.35	0.08	0.19	0.17	-0.25
acc_noun_naming_highmotion	-0.19	0.11	0.15	-0.20	0.04	0.05	0.06	-0.22	-0.03	-0.07	-0.21
acc_noun_naming_handact	-0.07	0.03	-0.16	0.04	0.20	0.07	0.18	0.01	0.17	-0.02	-0.05
acc_noun_naming_artefacts	0.42	0.15	0.12	-0.08	0.24	0.18	0.17	-0.04	-0.08	-0.09	-0.17

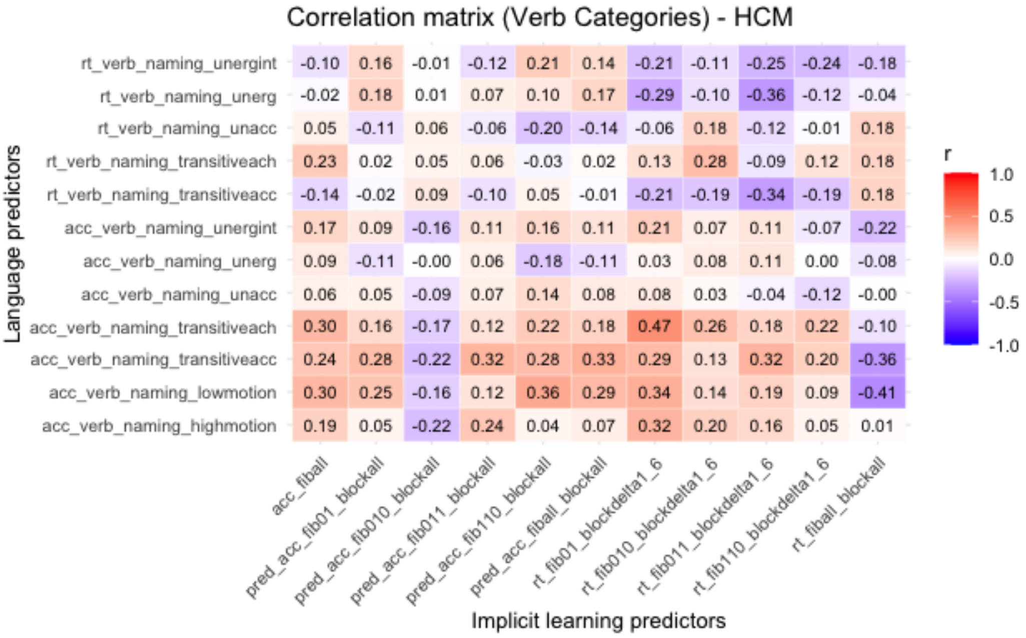
Figure 38. Correlation Matrix between Noun Linguistic Measures and Implicit Learning Metrics in HCM

Correlations between Verb Linguistic Measures and Implicit Learning Measures


Correlation matrix (Verb Categories) - PD

Language predictors	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_verb_naming_unergint	0.06	-0.06	0.04	0.23	-0.06	0.05	-0.15	-0.23	-0.15	-0.11	0.30
rt_verb_naming_unerg	-0.23	0.04	0.16	-0.10	-0.06	-0.01	-0.11	-0.05	-0.22	-0.24	0.61*
rt_verb_naming_unacc	-0.15	-0.13	0.12	-0.15	0.09	-0.15	-0.31	-0.29	-0.31	-0.31	0.51
rt_verb_naming_transitiveach	-0.00	-0.12	0.14	0.02	-0.02	-0.10	-0.09	0.03	0.02	0.02	0.38
rt_verb_naming_transitiveacc	-0.04	-0.23	0.21	-0.03	0.05	-0.17	-0.14	-0.10	-0.28	-0.14	0.35
acc_verb_naming_unergint	0.07	0.11	-0.09	0.10	-0.06	0.13	0.49	0.47	0.58*	0.71*	-0.35
acc_verb_naming_unerg	0.29	0.20	-0.23	0.16	-0.07	0.22	0.13	0.13	0.20	0.28	-0.52
acc_verb_naming_unacc	0.06	0.13	-0.24	-0.03	-0.07	-0.01	0.38	0.34	0.28	0.35	-0.41
acc_verb_naming_transitiveach	-0.22	0.14	0.05	-0.08	0.07	0.16	0.08	0.36	0.27	0.22	-0.09
acc_verb_naming_transitiveacc	0.00	-0.09	-0.05	0.13	-0.09	-0.10	-0.24	-0.06	-0.03	-0.09	0.16
acc_verb_naming_lowmotion	-0.05	0.07	-0.06	0.05	0.09	0.16	0.15	0.37	0.38	0.43	-0.33
acc_verb_naming_highmotion	0.06	0.16	-0.19	0.04	-0.16	0.04	0.29	0.31	0.31	0.33	-0.24

Figure 39. Correlation Matrix between Verb Linguistic Measures and Implicit Learning Metrics in PD


Correlation matrix (Verb Categories) - HCM

Language predictors	acc_fiball	pred_acc_fib01_blockall	pred_acc_fib010_blockall	pred_acc_fib011_blockall	pred_acc_fib110_blockall	pred_acc_fiball_blockall	rt_fib01_blockdelta1_6	rt_fib010_blockdelta1_6	rt_fib011_blockdelta1_6	rt_fib110_blockdelta1_6	rt_fiball_blockall
rt_verb_naming_unergint	-0.10	0.16	-0.01	-0.12	0.21	0.14	-0.21	-0.11	-0.25	-0.24	-0.18
rt_verb_naming_unerg	-0.02	0.18	0.01	0.07	0.10	0.17	-0.29	-0.10	-0.36	-0.12	-0.04
rt_verb_naming_unacc	0.05	-0.11	0.06	-0.06	-0.20	-0.14	-0.06	0.18	-0.12	-0.01	0.18
rt_verb_naming_transitiveach	0.23	0.02	0.05	0.06	-0.03	0.02	0.13	0.28	-0.09	0.12	0.18
rt_verb_naming_transitiveacc	-0.14	-0.02	0.09	-0.10	0.05	-0.01	-0.21	-0.19	-0.34	-0.19	0.18
acc_verb_naming_unergint	0.17	0.09	-0.16	0.11	0.16	0.11	0.21	0.07	0.11	-0.07	-0.22
acc_verb_naming_unerg	0.09	-0.11	-0.00	0.06	-0.18	-0.11	0.03	0.08	0.11	0.00	-0.08
acc_verb_naming_unacc	0.06	0.05	-0.09	0.07	0.14	0.08	0.08	0.03	-0.04	-0.12	-0.00
acc_verb_naming_transitiveach	0.30	0.16	-0.17	0.12	0.22	0.18	0.47	0.26	0.18	0.22	-0.10
acc_verb_naming_transitiveacc	0.24	0.28	-0.22	0.32	0.28	0.33	0.29	0.13	0.32	0.20	-0.36
acc_verb_naming_lowmotion	0.30	0.25	-0.16	0.12	0.36	0.29	0.34	0.14	0.19	0.09	-0.41
acc_verb_naming_highmotion	0.19	0.05	-0.22	0.24	0.04	0.07	0.32	0.20	0.16	0.05	0.01

Figure 40. Correlation Matrix between Verb Linguistic Measures and Implicit Learning Metrics in HCM

Since none of the correlations between linguistic and implicit learning measures was significant in healthy controls but some correlations between these capacities emerged in the PD group, we hypothesised that noun and verb naming were differentially modulated by implicit learning skills in the two groups. In other words, we asked "Does diagnostic group moderate the relationship between implicit learning ability and lexical retrieval speed?".

A multiple regression model tested whether implicit learning accuracy as measured through correct oculomotor anticipation was differentially related to noun naming reaction times across groups, controlling for overall motor response speed (rt_fiball_blockall). A *Group* x *Learning* interaction approached significance ($\beta = -2.52$, SE = 1.44, $p = .086$), indicating that higher implicit learning accuracy predicted faster naming reaction times in the PD group but not in controls (Figure 41). Similar results were obtained when analysing verb naming (Figure 42). The model controlled for general motor speed. A negative, near-significance interaction suggests a compensatory effect: PD participants who retain stronger implicit learning abilities are less slowed in language tasks. This trend is consistent with a compensatory mechanism, whereby stronger domain-general learning abilities mitigate lexical retrieval slowing in PD.

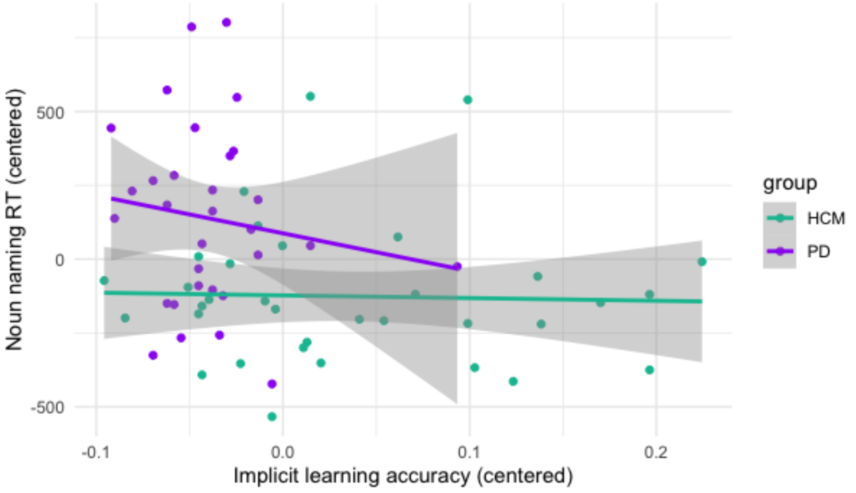


Figure 41. Interaction between implicit learning and group on noun naming RT

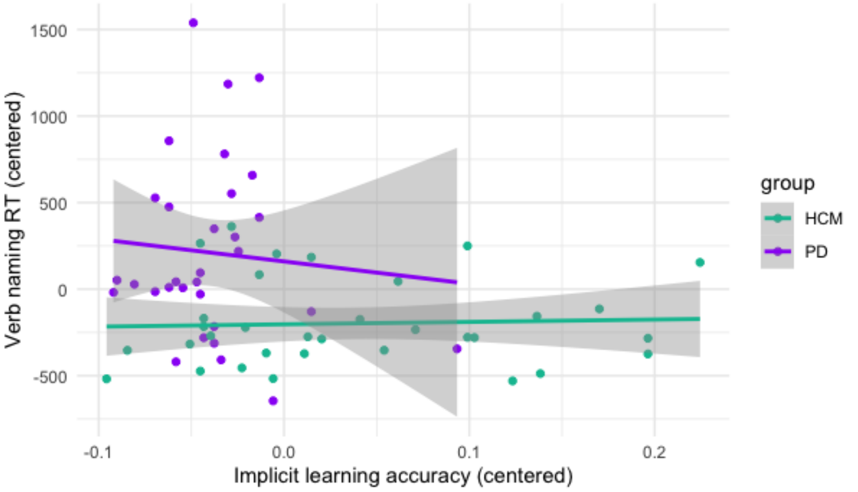


Figure 42. Interaction between implicit learning and group on verb naming RT

Appendix 4.2: Machine-Learning-Based Classification for Parkinson's Prediction

As the title of this dissertation suggests, the overarching aim of the present work was to explore the predictive potential of language competence and implicit learning in PD. Predictive modelling should ideally evaluated on new, unseen cases, that is, on future participants. In the present protocol, however, the first step consisted in identifying linguistic and implicit learning measures capable of discriminating between individuals with PD and neurotypical controls. To this end, we tested participants with an existing PD diagnosis to evaluate the robustness of linguistic and learning-based predictors.

In absence of "future cases" (i.e., individuals not yet assigned to either group), the prediction problem can still be statistically modelled using existing data. Supervised machine learning algorithms based on two-class classification are well suited to this purpose: they can be trained on one subset of existing data and subsequently evaluated on an independent subset withheld from the model during training. The usefulness of the derived predictors increases if they remain robust when applied to cases with less clearly defined symptomatology. In the present work, the predictive capacity of linguistic and implicit-learning measures was evaluated using this cross-validated testing approach.

Methods

Ninety-five linguistic and learning-based predictors were selected from our studies for each participant (see Table 21 for examples; the complete list of predictors is provided in Appendix 4.1), together with the binary outcome variable *Group* (PD vs. HCM), which was encoded as a binary factor (PD = positive; HCM = negative). The unique participant identifier column was removed prior to model fitting to prevent data leakage. All analyses were conducted in R (version 4.4.2).

Table 21. Examples of Predictor Variables

id	predictor	domain	task
1	acc_fib01	implicit learning	behavioural responses
2	acc_fib110	implicit learning	behavioural responses
3	acc_fib011	implicit learning	behavioural responses
4	acc_fib010	implicit learning	behavioural responses
5	acc_fiball	implicit learning	behavioural responses

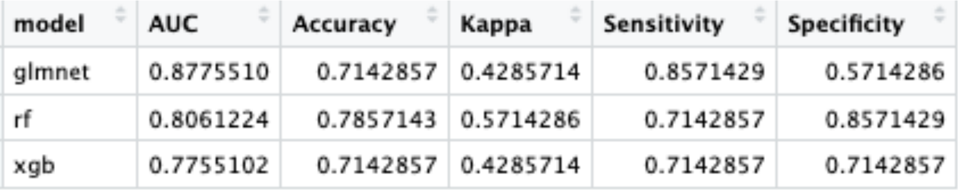
The dataset comprised 65 participants (31 PD, 34 HCM). A stratified split was applied using *createDataPartition* to preserve class balance, producing a training set (75%) and an independent test set (25%). Specifically, a sanity check confirmed that the training set included 24 PD and 26 HCM participants, while the test set included 7 PD and 8 HCM participants, confirming comparable group representation in each subset.

Three supervised classification algorithms were trained on the training data: regularised logistic regression (*glmnet* package), random forest (*randomForest*), and extreme gradient boosting (XGBoost) (*xgbTree* package). Model tuning and internal validation were performed via repeated 5-fold cross-validation (10 repeats) implemented via the *trainControl* function in the *caret* package. Each final model was then evaluated on the independent test set, and the performance metrics for model comparison included Area Under the ROC Curve (AUC), Accuracy, Cohen's Kappa, Sensitivity, and Specificity.

Results

Across repeated cross-validation, all three models achieved comparable ROC values (median ROC = 0.80-0.85) with no statistically significant differences (Bonferroni-adjusted $p > 0.05$). When tested on the independent test set, the models showed the performance summarised in Table 22.

Table 22. Performance Metrics for Model Comparison



model	AUC	Accuracy	Kappa	Sensitivity	Specificity
glmnet	0.8775510	0.7142857	0.4285714	0.8571429	0.5714286
rf	0.8061224	0.7857143	0.5714286	0.7142857	0.8571429
xgb	0.7755102	0.7142857	0.4285714	0.7142857	0.7142857

The Random Forest model achieved the best overall balance between sensitivity and specificity (Accuracy = 0.79; AUC = 0.81). The GLMNet model yielded slightly higher discriminative ability (AUC = 0.88), albeit at the expense of specificity, while XGBoost performance was comparable though marginally lower overall.

Across models, the twenty most influential predictors were extracted based on their relative importance (Figure 43).

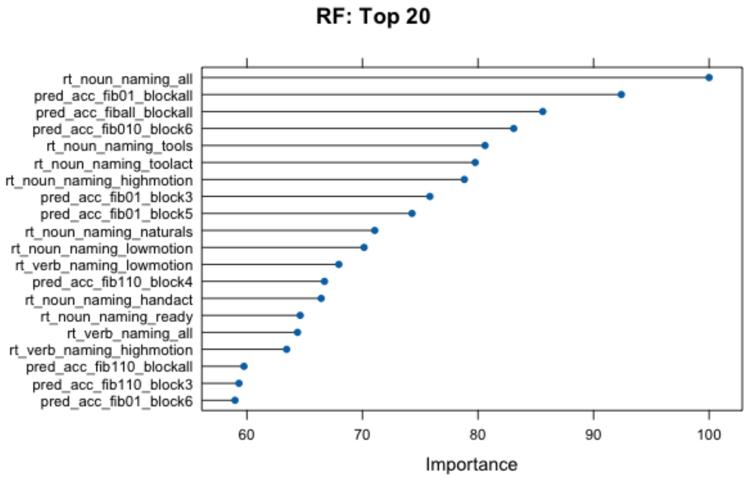


Figure 43. Top 20 Predictors in the Random Forest Model

It is noteworthy that all 95 predictors employed, of which the 20 most relevant are displayed above, were exclusively linguistic (derived from the naming task) and learning-related (from the implicit learning task). In other words, without any additional demographic or clinical information about participants, the model successfully classified individuals as neurotypical or affected by PD solely on the basis of language and implicit-learning features. Among the most relevant predictors, reaction times in the naming task, particularly for nouns referring to tools, tool-related actions, and high-motion items, emerged as especially informative. Likewise, accuracy in predictive eye movements towards target AOIs during the implicit learning task based on the Fibonacci grammar contributed substantially to model performance.

Given the modest sample size (65 participants in total, of which 48 were used for model training), these results should be interpreted with caution. A larger dataset would provide greater statistical power and improve model generalisation, with more stable performance estimates. Nevertheless, the current findings provide a promising proof of concept: measures of language competence and implicit learning abilities can reliably distinguish between individuals with PD and healthy controls.