

# The unseen risk: How visual impairments impact car driving in Parkinson's disease

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## Abstract

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Automobile driving is a complex sensorimotor activity that depends on the continuous integration of visual input, attentional allocation, executive control, and motor execution. Specifically, safe driving necessitates the continuous extraction, selection, and transformation of visual information to guide steering, regulate speed, maintain lane position, anticipate hazards, and make rapid decisions in dynamic environments.

Consequently, as driving a motor vehicle demands the effective integration of multiple visual functions, visual impairments may have significant ramifications for driving performance and safety. A minimum of 75% of individuals diagnosed with Parkinson's disease (PD) encounter one or more visual disturbances during the course of the disease. A mounting body of evidence indicates that drivers with PD demonstrate increased variability in lane position, delayed hazard detection, impaired visual scanning strategies, and reduced adaptability under conditions of high cognitive load or degraded visual environments. This results in a higher frequency of safety errors, poorer performance in driving simulators and on-road assessments, and a significantly increased likelihood of failing formal fitness-to-drive evaluations when compared with neurologically healthy drivers. Consequently, automobile driving has emerged as a critical real-world context in which visual deficits in PD translate directly into safety risks and loss of functional independence. The objective of this chapter is to undertake an examination of the role that visual information plays in driving and disease-related consequences of lower vision among individuals with PD. In this chapter, an exhaustive review of the primary visual impairments associated with PD is conducted. The interaction of these visual impairments with cognitive and motor deficits, and its subsequent impact on driving behavior, driving errors, and performance in simulated and on-road assessments, is then discussed. Finally, the chapter integrates evidence from experimental, clinical, and applied driving research to propose a conceptual framework in which visual and cognitive dysfunctions, rather than motor severity alone, affect automobile driving performance in individuals with PD.

## Introduction

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Driving a car is a demanding activity, requiring optimal visual perception, selective attention, and effective visuomotor integration. Vision is the predominant sensory modality that guides automobile driving, as safe navigation is dependent on the continuous extraction and interpretation of visual information. Specifically, safe driving necessitates the continuous extraction, selection, and transformation of visual information to guide steering, regulate speed, maintain lane position, anticipate hazards, and make rapid decisions in dynamic environments (Alvarez; Classen, 2018; Gibson, 1979). Consequently, deficits in vision may result in an increased frequency of car accidents and driving errors.

Epidemiological and clinical studies indicate that at least 75% of individuals with PD experience one or more visual disturbances over the course of the disease (Archibald *et al.*, 2011; Hamedani; VanderBeek; Willis, 2019). These disturbances extend beyond reduced visual acuity, encompassing impairments in contrast sensitivity, motion perception, visual processing speed, and visual attention (Armstrong, 2015; Halperin *et al.*, 2021; Uc *et al.*, 2009b). These impairments worsen with disease progression (Leissner *et al.*, 2014). Despite their clinical relevance, visual impairments remain under-recognized and under-assessed in routine neurological care. The identification of these non-motor manifestations can be particularly challenging due to their often subtle nature, gradual progression, and potential to go unnoticed by clinicians, caregivers, and even individuals with PD themselves (Bonnet *et al.*, 2012).

Visual impairments have been shown to interact with cognitive slowing and executive dysfunction, creating a constellation of deficits that can critically undermine driving safety in PD. An

accumulating body of research has demonstrated that individuals with PD exhibit an increased propensity to commit more safety errors and demonstrate diminished performance in car driving simulators and on-road assessments (Classen, 2014; Devos *et al.*, 2013b; Uc *et al.*, 2007). Furthermore, individuals with PD exhibit a higher probability of failing formal fitness-to-drive evaluations in comparison to neurologically healthy drivers, attributable to limitations in visual acuity (Classen, 2014; Devos *et al.*, 2013b; Uc *et al.*, 2007). Notably, these driving difficulties are evident even in mild to moderate stages of PD and become particularly pronounced under conditions of increased visual or cognitive demand, such as low-contrast environments, navigation tasks, or complex traffic situations (Stolwyk *et al.*, 2006; Uc *et al.*, 2009b). Consequently, automobile driving has emerged as a critical real-world context in which visual deficits in PD translate directly into safety risks and loss of functional independence.

In consideration of the aforementioned context, the objective of this chapter is to examine the role of visual information in driving and disease-related consequences of lower vision among individuals with PD. The initial section of this chapter examines the manner in which visual impairments, when interacted with cognitive and motor deficits, influence driving behavior, errors, and performance in simulated and on-road assessments. In the sequence, the primary visual impairments associated with PD are reviewed, including deficits in contrast sensitivity, visual attention, motion perception, and visual processing speed. The relationship between these visual deficits and automobile driving performance is then presented. In the subsequent section, we direct our attention to the phenomenon of perception-action coupling during driving, emphasizing alterations in gaze behavior, visual scanning strategies, and oculomotor control in individuals diagnosed with PD. Finally, the final chapter integrates evidence

from experimental, clinical, and applied driving research to propose a conceptual framework in which visual and cognitive dysfunctions, rather than motor severity alone, are the primary determinants of driving safety, driving cessation, and functional mobility in individuals with PD.

## **Interaction between vision and driving**

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Vision is the predominant sensory modality that facilitates safe driving, providing approximately 90% of the information necessary to guide steering, maintain lane position, detect hazards, and regulate speed in dynamic traffic environments (Groeger, 2013; Johnson *et al.*, 2014). Driving a car is fundamentally a visuomotor task. In this task, a driver continuously extracts and interprets visual cues, including optic flow (i.e., the apparent motion of objects as perceived by the eye); contrast (i.e., the difference in brightness or darkness between objects); motion (i.e., the movement or movement patterns of objects); and spatial layout (i.e., the arrangement or organization of objects in physical space). These visual cues are processed by the driver's brain, which then generates timely motor responses, or the actions of the driver's limbs in response to the stimuli received from the environment. Consequently, deficits in any domain of visual function can propagate through the entire perception-action loop, thereby compromising hazard detection, decision-making, and vehicle control.

The visual system plays a pivotal role in the act of driving, with multiple components working in concert to facilitate safe and effective operation of the vehicle. Visual acuity facilitates the recognition of road signs, pedestrians, and vehicles at a distance, while contrast sensitivity enables drivers to detect low-contrast

objects, road edges, and lane markings, particularly under fog, dusk, or glare conditions (Owsley; McGwin, 2010). Depth perception and stereopsis are critical for evaluating distances during overtaking maneuvers, merging, and reacting to braking vehicles (Horswill *et al.*, 2010). Peripheral vision facilitates the early detection of lateral hazards and contributes to lane-keeping performance by providing continuous information about the vehicle's position relative to the road boundaries (Wood *et al.*, 2016).

The relative contribution of visual mechanisms becomes even more apparent under challenging environmental conditions. Poor illumination, fog, and glare have been shown to degrade contrast sensitivity and slow visual processing, disproportionately impairing drivers with existing visual or cognitive deficits (Owens; Wood; Carberry, 2010). In such circumstances, visual information becomes convoluted and open to interpretation, necessitating additional cognitive resources for its interpretation. Drivers with intact vision have the capacity to compensate for visual impairments through predictive gaze behaviors and strategic slowing. In contrast, individuals with compromised visual systems, including those with PD, age-related decline, or other neurodegenerative conditions, exhibit amplified performance decrements.

The role of visual attention is equally significant, as it determines the efficiency with which drivers can select relevant stimuli from complex scenes. The Useful Field of View (UFOV), a metric of processing speed and attentional distribution, has been identified as a significant predictor of real-world crash risk in older drivers (Ball *et al.*, 2006). Drivers must rapidly shift their gaze between various targets, including mirrors, the speedometer, pedestrians, and cross-traffic intersections. Efficient gaze strategies enable experienced drivers to anticipate

hazards and maintain situational awareness. In contrast, reduced attentional capacity or slowed visual processing leads to delayed reactions and an increased likelihood of error (Liu *et al.*, 2022).

The integration between vision and motor output is especially critical for car driving. The steering control mechanism is contingent upon optic flow information, which is attributed to global patterns of visual motion that specify heading direction and vehicle trajectory (Land; Lee, 1994). Subtle deviations in optic flow have been demonstrated to guide micro-corrections in steering. When visual motion processing is impaired, there is a marked increase in steering variability and lane-position instability (Wilkie; Wann, 2006). Furthermore, the braking responses of the subjects in this study were found to be contingent upon the precise processing of looming cues. These cues, as previously defined by Lee (1976), serve to signal the imminent velocity of objects and vehicles in the forward direction. Consequently, deficits in motion perception or slowed visual processing directly translate into delayed braking and an increased risk of collision.

Collectively, these findings underscore the notion that driving a car is not solely a motor skill but rather a highly visual task that demands the rapid and precise extraction of environmental information. Vision exerts a profound influence on various facets of driving behavior, ranging from tactical navigation to rapid hazard responses. Consequently, impairments in visual acuity, contrast sensitivity, peripheral awareness, motion processing, or visual attention significantly compromise driving safety. Therefore, a comprehensive understanding of these mechanisms is imperative for evaluating car driving fitness in PD, where visual impairments are prevalent and frequently precede significant motor symptoms.

## **Vision-related impairments affecting driving in Parkinson's disease**

PD is a progressive neurodegenerative disorder characterized by the degeneration of dopamine-producing neurons in the substantia nigra pars compacta (Poewe *et al.*, 2017). Individuals with PD typically present the cardinal motor symptoms of bradykinesia, tremor, rigidity, and postural instability (Postuma *et al.*, 2015). However, beyond motor deficits, PD also causes a wide range of non-motor symptoms, including sensory and perceptual impairments (Halperin *et al.*, 2021).

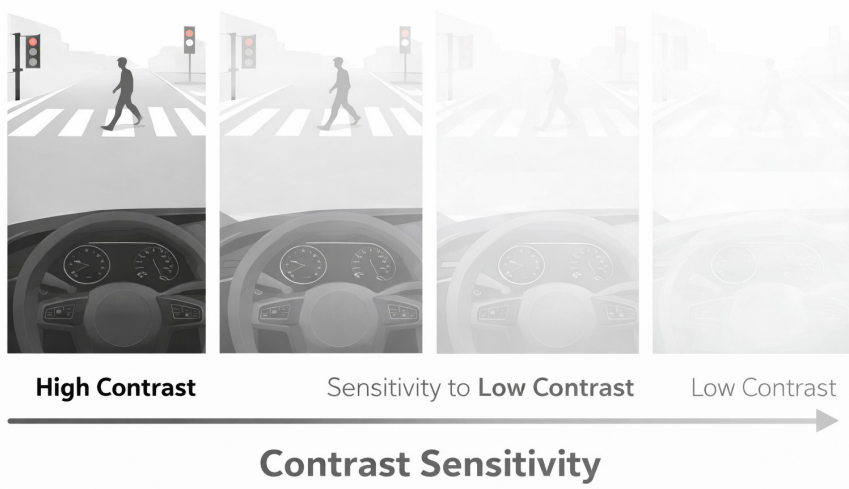
Visual impairment is a prevalent non-motor manifestation in PD, encompassing various levels of processing from basic sensory function to higher-order visual processing (Weil *et al.*, 2016). This condition directly impacts driving-related abilities. Therefore, a comprehensive understanding of the visual impairments associated with PD is imperative to develop effective strategies to mitigate these impairments. Instead of providing an exhaustive review of all visual alterations reported in PD, this section focuses specifically on those impairments that have been demonstrated to be relevant to car driving performance and road safety.

### **Contrast sensitivity**

Reduced contrast sensitivity has been identified as one of the most consistent visual impairments in PD (Savitt; Aouchiche, 2020). As demonstrated in the research by Weil *et al.* (2016), losses are particularly evident at medium and high spatial frequencies and occur in both central (foveal) and peripheral vision. Structurally, contrast sensitivity has been found to correlate with the thinning of inner retinal layers, thereby suggesting a retinal dopaminergic contribution (Nieto-Escamez;

Obrero-Gaitán; Cortés-Pérez, 2023; Polo *et al.*, 2016). Figure 1 presents a simulated example of contrast sensitivity during car driving.

From a driving perspective, contrast sensitivity is an important factor for mobility and fitness-to-drive in individuals with PD (Alvarez; Classen, 2018). Contrast sensitivity plays a pivotal role in the detection of lane markings, pedestrians, obstacles, and road signs, particularly in low-contrast environments such as fog, dusk, rain, or nighttime driving conditions (Alvarez; Classen, 2018; Savitt; Aouchiche, 2020). Reduced contrast sensitivity has been associated with diminished on-road performance and elevated safety errors in drivers with PD (Alvarez; Classen, 2018; Uc *et al.*, 2005). Impaired contrast processing has been demonstrated to compromise hazard detection, edge perception, and optic flow interpretation. These processes are all essential for maintaining stable lane position and anticipating environmental changes.



**Figure 1.** Example of contrast sensitivity during car driving.

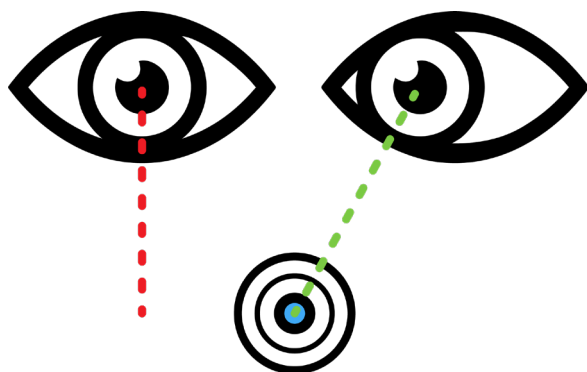
## **Visual processing speed and useful field of view**

Research has demonstrated a strong correlation between reduced visual processing speed and reduced UFOV with car driving performance in PD (Classen *et al.*, 2009; Uc *et al.*, 2011). These deficits are indicative of diminished efficiency in the extraction and prioritization of visual information across central and peripheral regions. Driving necessitates the rapid detection of unexpected hazards, the monitoring of mirrors and blind spots, and the simultaneous processing of multiple stimuli, such as traffic lights, vehicles, and pedestrians. A reduced UFOV imposes limitations on the spatial extent over which information can be processed effectively, resulting in increased reaction time and the probability of missing critical events. A notable finding is the capacity of UFOV performance to predict pass/fail outcomes in on-road driving assessments in PD (Alvarez; Classen, 2018).

## **Oculomotor dysfunction and convergence insufficiency**

Oculomotor abnormalities, particularly convergence insufficiency (CI) (Figure 2) and its associated abnormalities, are considered to be among the most prevalent oculomotor disturbances in PD (Ekker *et al.*, 2017). Other impairments associated with CI include near-vision blurriness (Sun *et al.*, 2023) and issues with depth perception (Borm *et al.*, 2020). These impairments are critical for evaluating distances during lane changes, merging, and parking maneuvers. Vergence movements—that is, simultaneous eye movements in opposite directions—and hypometric saccades have been shown to impede efficient visual scanning (Archibald *et al.*, 2011). In the context of driving, reduced saccade amplitude has been shown to limit environmental exploration, impair mirror checking

behavior, and reduce situational awareness (Sun *et al.*, 2023). Convergence deficits have also been demonstrated to contribute to intermittent diplopia (Savitt; Aouchiche, 2020; Sun *et al.*, 2023), further disrupting spatial estimation and increasing uncertainty in complex traffic situations.



**Figure 2.** An example of convergence insufficiency, a condition marked by the inability of the eyes to move in unison, manifests as a disruption in the synchronization of ocular movements, thereby impeding the efficient scanning of visual targets.

## Motion perception and optic flow processing

The act of driving a car is contingent upon the capacity to accurately perceive motion and process visual information to estimate velocity, self-motion, and the relative movements of surrounding vehicles. Deficits in motion cue extraction have been demonstrated to contribute to unstable steering, inaccurate speed regulation, and difficulty anticipating moving hazards. In PD, impairments in motion perception and spatiotemporal processing have been documented (Montse *et al.*, 2001; Weil *et al.*, 2016). In the context of adverse visual conditions, these impairments become more pronounced, contributing to increased lane variability and collision risk (Uc *et al.*, 2009c).

## Visual hallucinations

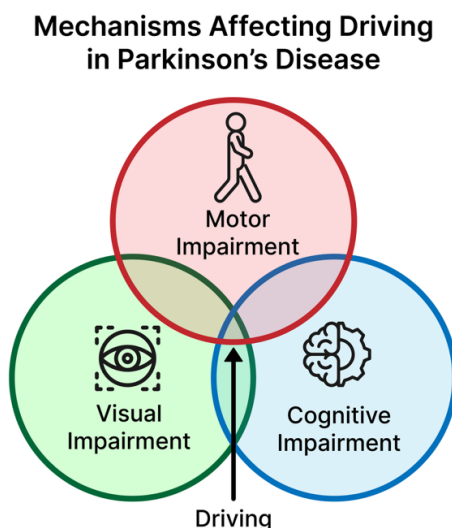
Visual hallucinations in PD range from minor phenomena, such as presence hallucinations (the sensation that someone is nearby), passage hallucinations (brief peripheral shadows), and visual illusions, to well-formed complex images of people, animals, or objects. Visual hallucinations have been demonstrated to be associated with cognitive decline and visuospatial dysfunction in PD (Archibald *et al.*, 2011; Mosimann *et al.*, 2006). From a driving perspective, hallucinations and visual misperceptions represent a direct safety risk. Peripheral passage hallucinations have the potential to be misinterpreted as pedestrians or vehicles, which can result in abrupt braking or evasive steering. Illusions have the potential to distort perception of road markings, obstacles, or shadows, which can result in inappropriate motor responses (Archibald *et al.*, 2011). Even when hallucinations are transient or insight is preserved, their occurrence increases cognitive load, diverts attentional resources, and reduces driver confidence (Mosimann *et al.*, 2006), thereby compromising sustained attention and situational awareness during complex traffic situations.

## Car driving performance and determinants of safety in PD

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Safe driving necessitates the seamless integration of motor, visual, and cognitive processes (Figure 3). Consequently, this multifaceted process constitutes a sophisticated perception-action system that facilitates the driver's ability to regulate speed, maintain lane position, detect hazards, and make swift decisions in dynamic environments (Anstey *et al.*, 2005).

In PD, these systems are frequently compromised due to neurodegeneration affecting the basal ganglia, fronto-striatal networks, and dopaminergic pathways (Chaudhuri; Schapira, 2009; Owen, 2004). These impairments are not confined to advanced stages of the disease. Even individuals with mild to moderate PD exhibit deficits that can compromise car driving safety, particularly under cognitively demanding or perceptually challenging conditions (Stolwyk *et al.*, 2006; Uc *et al.*, 2009c).



**Figure 3.** General mechanism that affects driving in individuals with Parkinson's disease.

### **General driving performance deficits in PD**

A substantial body of evidence suggests that drivers with PD exhibit a higher frequency of safety-critical errors and demonstrate impaired vehicle control in comparison to healthy controls. Across both simulator and on-road studies, these drivers exhibit slower reaction times, reduced hazard detection ability, poorer lane maintenance, and greater difficulty in

adapting speed to traffic demands (Devos *et al.*, 2013b; Uc *et al.*, 2007, 2009a). These deficits can be broadly categorized into two distinct types: tactical and operational errors.

Tactical errors, defined as difficulties in planning and adapting driving behavior to dynamic traffic demands, have been consistently documented in drivers with PD during on-road and simulator-based studies (Amick; Grace; Ott, 2007; Devos *et al.*, 2013a). These errors include inappropriate lane changes, difficulty controlling speed, and misjudgments during complex maneuvers such as intersections and turns. Previous studies have indicated that these errors occur with greater frequency in individuals with PD than in neurologically healthy drivers. This elevated frequency is particularly evident in situations that require rapid decision-making and behavioral flexibility (Amick; Grace; Ott, 2007; Classen, 2014). Furthermore, a strong correlation has been demonstrated between tactical driving errors and impairments in executive function, divided attention, and reduced cognitive flexibility. These findings are indicative of dysfunction within fronto-striatal circuits in individuals with PD (Amick; Grace; Ott, 2007; Devos *et al.*, 2013a).

Operational errors are indicative of impairments in the moment-to-moment control of the vehicle and are also disproportionately observed in drivers with PD across experimental and naturalistic driving studies (Stolwyk *et al.*, 2006; Uc *et al.*, 2007). According to the findings of Stolwyk *et al.* (2006) and Uc *et al.* (2007), individuals with PD exhibit protracted hesitation during traffic entry, inadequate acceleration upon entering traffic, deficits in sustained attention, and elevated variability in lateral lane position in comparison with control drivers. These operational failures may be associated with PD-related bradykinesia, reduced motor automaticity, and deficits in continuous perceptual monitoring. This underscores the notion

that motor and sensory dysfunctions, hallmarks of PD, directly impede the execution of driving actions (Stolwyk *et al.*, 2006; Uc *et al.*, 2007).

These observations are corroborated by the findings of simulator studies. Individuals with PD exhibit not only slower reaction times but also reduced driving exposure and higher levels of depression (Crizzle *et al.*, 2013). These factors correlate with decreased driving frequency and mileage. A reduced level of exposure to driving-related activities may potentially exacerbate existing deficiencies in driving skills over time. This phenomenon can create a self-perpetuating cycle, whereby a lack of consistent practice serves to compound existing skills deficits. Furthermore, environmental conditions have been demonstrated to exert a substantial influence on performance outcomes. In conditions characterized by reduced visibility, such as fog, darkness, or low-contrast environments, individuals with PD have been observed to demonstrate heightened lateral variability in their driving behavior. This heightened variability is accompanied by a diminished steering control capacity and an elevated frequency of simulated collisions (Uc *et al.*, 2009b). These findings underscore that driving deficits in PD are not static but are exacerbated when sensory input becomes degraded or cognitive demands increase.

Driving in adverse environmental conditions has been demonstrated to exacerbate perceptual deficits in individuals with PD. In conditions characterized by fog, low light, or reduced contrast, individuals with PD demonstrate significant instability in lateral lane position, diminished steering precision, and an elevated probability of collisions (Möller *et al.*, 2002; Uc *et al.*, 2009b). These impairments are indicative of difficulties in rapidly extracting motion cues, detecting edges, and interpreting optic flow signals. These visual capacities are particularly susceptible

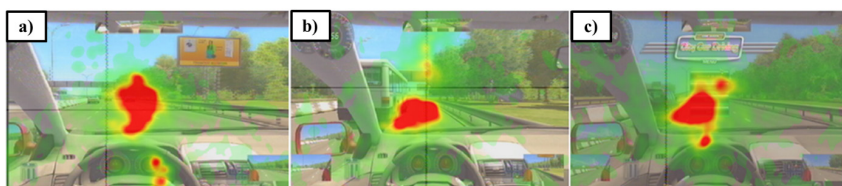
in individuals with PD due to the slowed rate of visual processing. This interpretation is further substantiated by the observation that individuals with PD demonstrate prolonged reaction times to unanticipated hazards, augmented navigation errors, and diminished performance at intricate intersections, particularly in circumstances that demand elevated visual and cognitive faculties (Piras *et al.*, 2022; Uc *et al.*, 2007). Importantly, these driving impairments correlate more strongly with cognitive-perceptual deficits than with motor severity, reinforcing the notion that driving difficulties in PD primarily arise from dysfunction in visual and cognitive domains rather than from movement-related impairments alone.

### **Combined effects of Parkinson's disease and aging on driving performance**

The interaction between PD-related impairments and natural aging processes plays an important role in shaping driving outcomes. Age-related declines in vision, attention, and processing speed are well documented in the general population. These factors overlap with the cognitive and perceptual deficits characteristic of PD. Gotardi *et al.* (2022) compared three groups of drivers (PD, healthy older adults, and young adults) during a simulated highway driving task requiring speed maintenance and collision avoidance. The performance of both the PD group and the older healthy group was significantly lower than that of the young adult group, as evidenced by their greater difficulty in maintaining target speed and avoiding hazards (Figure 4). Notably, no substantial disparities were observed between the PD and the older, healthy groups. This finding indicates that specific components of impaired performance in PD are attributable to mechanisms shared with normal

aging, particularly visual processing inefficiency, attentional narrowing, and reduced psychomotor speed.

This observation does not negate the impact of PD; rather, it underscores the notion that disease-related deficits frequently manifest in the same functional domains that are already susceptible to age-related degeneration. In practical terms, this suggests that even mild PD may cause older individuals to exceed a threshold where compensatory strategies are no longer adequate to ensure safe driving. The combined influence of aging and PD likely accelerates the degradation of driving-relevant skills, emphasizing the importance of sensitive assessments capable of distinguishing disease-specific problems from those associated with normative aging.



**Figure 4.** Heat maps representing the relative density of visual fixation for: a) younger drivers; b) older healthy drivers; and c) PD drivers. Cooler colors (green) indicate less visual activity, while hotter colors (red) indicate areas where more time was spent gazing. *Source: Gotardi et al. (2022); used with permission.*

### **Influence of medication and motor severity**

While PD is characterized predominantly as a motor disorder, the severity of motor impairment does not consistently predict driving performance. Research has indicated that scores on the Unified Parkinson's Disease Rating Scale (UPDRS), particularly the motor subscales, demonstrate an absence or instability of correlation with actual driving performance (Devos *et al.*, 2007; Uc; Rizzo, 2008; Worringham *et al.*, 2006). This dissociation can be attributed to the fact that driving a car is heavily dependent on

visual and cognitive functions, which are only partially amenable to dopaminergic therapy.

The findings on medication effects are contradictory. A previous study demonstrated that individuals with PD exhibit significant impairments during “wearing-off” periods of levodopa and demonstrate improvements under “best-ON” medication states, particularly when administered with opicapone (Marano *et al.*, 2024). These results suggest that optimized dopaminergic treatment may enhance general car driving behavior, perhaps by improving motor initiation, alertness, and fine-control movements. However, other studies have reported limited or no effects of dopaminergic medication on higher-level perceptual tasks relevant to driving, such as object discrimination or distance perception (Anderson; Stegemöller, 2020; Bernardinis *et al.*, 2021). These findings underscore a salient point: although dopaminergic therapy enhances motor output, it does not inherently normalize cognitive or perceptual functions that are critical for driving. Moreover, the administration of dopaminergic medications may introduce new risks. Excessive daytime sleepiness and sudden-onset sleep episodes (sometimes occurring without warning) pose serious threats to road safety (Álvarez, 2016; Möller *et al.*, 2002; Uc; Rizzo, 2008). Although rare, the unpredictable nature of sleep attacks necessitates close observation by clinicians, family members, and the drivers themselves. The variability of medication effects further complicates the decision-making process surrounding driving fitness in PD, highlighting the need for functional assessments that extend beyond motor symptoms.

### **Predictors of passing or failing driving assessments**

Across a variety of studies, visual and cognitive functions have been identified as the strongest predictors of real-world

car driving performance in individuals with PD, surpassing motor factors. This finding aligns with the broader body of literature on older drivers, which demonstrates that perceptual and attentional measures are more effective than traditional motor assessments in predicting on-road performance and crash risk (Ball *et al.*, 2006; Owsley; McGwin, 2010). Research has demonstrated that driving impairment in PD is fundamentally linked to deficits in higher-order cognitive control rather than to motor slowing alone (Devos *et al.*, 2013b; Uc *et al.*, 2007). Safe car driving necessitates the continuous updating of environmental information, the flexible adaptation to unexpected events, and the coordination of multiple task demands. Consequently, even mild executive dysfunction can substantially compromise real-world driving performance (Amick; Grace; Ott, 2007; Stolwyk *et al.*, 2006). Consequently, cognitive screening measures, particularly those assessing attentional flexibility and processing speed, should be considered central components of fitness-to-drive evaluations in PD (Alvarez; Classen, 2018; Classen, 2014).

### **Car driving cessation**

Individuals with PD demonstrate a higher prevalence of car driving cessation compared to healthy controls. As demonstrated by Uc *et al.* (2011), individuals with PD are observed to have a fivefold elevated probability of discontinuing driving activity prior to the anticipated timeline. Predictors of driving cessation include advanced age, depressive symptoms, prior collisions, compensatory driving habits (e.g., avoiding night driving), low mileage, and deficits in visual or cognitive domains. These findings illustrate that driving cessation often results from a combination of psychological, functional, and environmental factors, rather than from disease severity alone.

## The perception–driving interaction in PD: the role of visual information

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Driving a car is an inherently perceptual activity that depends on the continuous extraction and interpretation of visual information (i.e., driver's ability), including optic flow, edge detection, and spatial relationships, as well as the allocation of attention across multiple sources and the translation of perceptual input into coordinated motor responses. Evidence from both driving simulator and on-road studies demonstrates that individuals with PD exhibit atypical visual attention and gaze behavior during driving tasks. In comparison with younger drivers, who exhibit efficient gaze strategies focused on task-relevant elements such as the road ahead, surrounding vehicles, and the speed information, drivers with PD demonstrate highly variable and often erratic fixation patterns. Specifically, these drivers direct their gaze toward irrelevant areas while failing to sustain attention on critical stimuli (Gotardi *et al.*, 2022). A comparison of drivers with PD and healthy older adults reveals that the former exhibit poorer top-down attentional control and less effective visual exploration of the driving environment (Gotardi *et al.*, 2022).

Complementary research has revealed associated perceptual distortions to these altered gaze patterns. Individuals with PD exhibit slower visual processing speed, reduced useful field of view, and difficulty integrating multiple visual cues necessary for precise speed regulation and lateral stability (Halperin *et al.*, 2021; Owsley; McGwin, 2010). However, this does not lead to a complete breakdown, as an additional challenge emerges: perceptual overconfidence. Individuals with PD exhibited a tendency to overestimate the accuracy of their visual judgments, thereby creating a discrepancy between their subjective confidence and

their actual perceptual ability (Halperin *et al.*, 2021). In traffic environments that demand precise estimations of velocity, distance, and temporal metrics, such as overconfidence, may precipitate the occurrence of unsafe decisions, particularly in circumstances that necessitate expeditious responses (Crundall; Underwood, 2011). This discrepancy between perceived and actual ability has been demonstrated to compromise driving safety by impeding self-regulation and adaptive behavior.

At the neurological level, gaze and scanning abnormalities in PD extend beyond basic oculomotor hypometria. Individuals with PD exhibit reduced saccade amplitudes during visual scanning tasks that rely on memory-guided eye movements, while visually guided reflexive saccades remain relatively preserved (Archibald *et al.*, 2011). This pattern suggests that deficits emerge predominantly from impaired internal cueing and sequencing of eye movements, as opposed to from fundamental motor execution. Such dysfunction has been shown to restrict the effective visual scanning range, reduce situational awareness, and limit the driver's ability to monitor the complex spatial layout of the road environment (Crundall; Underwood, 2011; Uc *et al.*, 2009a).

These findings are consistent with contemporary models of basal ganglia function, which both the goal-directed and the stimulus-response habitual mode of action is regulated by basal ganglia (Redgrave *et al.*, 2010). As stated by Haber (2016), the basal ganglia and their projections to cortical areas (primarily the sensorimotor cortex) play a critical role in processing sensory afferent inputs necessary for skilled movement (Borich *et al.*, 2015). The basal ganglia have been demonstrated to play a role in action selection and gating through cortico-striato-thalamo-cortical loops (Alexander; Crutcher, 1990; Mink, 1996). Consequently, dopaminergic depletion in PD disrupts the timing,

scaling, and sequencing of internally generated actions, impairing the prioritization of task-relevant sensory input and weakening the coupling between perception and motor output (Redgrave *et al.*, 2010; Wu; Hallett, 2005). Furthermore, the basal ganglia provide anatomical and functional substrates that influence higher-order cognitive aspects of motor control via their cortical connections (Leisman; Braun-Benjamin; Melillo, 2014). The basal ganglia interact with the cerebellum, which contributes to timing and sensory acquisition and is involved in the prediction of the sensory consequences of action (Festini *et al.*, 2015). Moreover, the basal ganglia-cortical-cerebellar pathways play a pivotal role in cognitive processes that orchestrate movement strategies (Haber, 2016). In summary, these impairments in basal ganglia caused by PD affect sensorial inputs, movement planning and motor output during car driving. This results in impaired proactive allocation of visual attention, inefficient visual scanning strategies, reduced ability to anticipate hazards, late braking, reduced ability to change car direction, among others (Land; Lee, 1994; Uc *et al.*, 2009a), which are essential for continuous vehicle control and safe navigation.

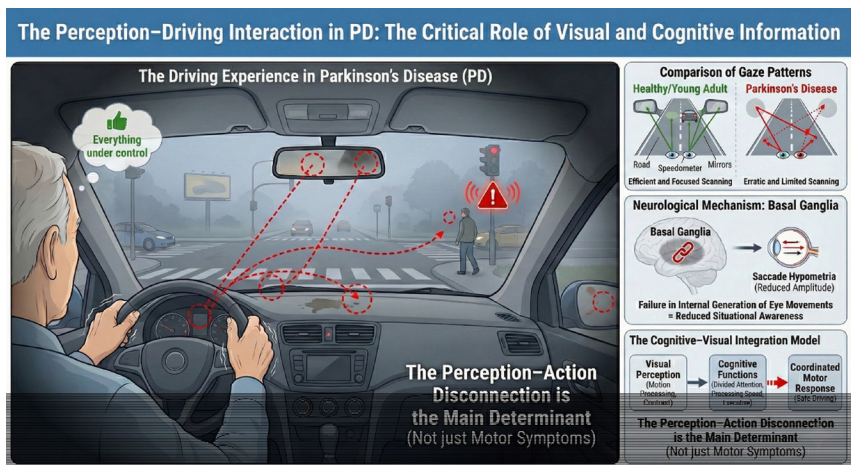
## **Final remarks**

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This chapter has synthesized compelling evidence that visual dysfunction is a central, and often overlooked, determinant of car driving performance in PD. Our understanding of PD has evolved from a narrow perspective, considering it exclusively as a motor disorder, to a more comprehensive view that recognizes it as a condition that significantly disrupts the fundamental perception-cognition-action cycle necessary for safe car driving (Redgrave *et al.*, 2010). Visual impairments

in PD are multifaceted, ranging from basic deficits in contrast sensitivity and convergence (Ekker *et al.*, 2017; Weil *et al.*, 2016) to complex issues in visual cue integration and the emergence of visual hallucinations (Montse *et al.*, 2001; Mosimann *et al.*, 2006). It is imperative to acknowledge that these issues are not merely isolated occurrences; rather, they directly compromise fundamental elements of driving, including lane maintenance, hazard detection, and efficient visual scanning (Alvarez; Classen, 2018; Uc *et al.*, 2009a).

The evidence supports a comprehensive model in which visual-cognitive integration, rather than motor impairment, emerges as the primary determinant of driving performance in PD. Visual perception has been shown to predict lateral stability and lane maintenance, while cognitive functions such as divided attention, processing speed, and executive control have been demonstrated to predict hazard detection, adaptive speed regulation, and tactical maneuvering. Executive functions play an additional role in route planning, multitasking, and decision-making during complex interactions with other road users. As demonstrated in Figure 5, the integrity of perceptual-cognitive integration is pivotal in determining a driver's ability to extract meaningful information from the environment, select the appropriate response, and translate this information into coordinated motor action. In PD, the disruption of this perceptual-cognitive integration instigates a cascade of perceptual, cognitive, and operational errors that collectively compromise driving safety. It is imperative to comprehend these mechanisms to develop precise assessment instruments, targeted interventions, and evidence-based guidelines that facilitate safe mobility for individuals living with PD.



**Figure 5.** The perception–driving interaction in Parkinson’s Disease. The central panel illustrates the driving experience and perceptual deficits. Side panels detail: (A) Comparison of gaze patterns between healthy adults and PD drivers; (B) Basal ganglia involvement in saccadic control; and (C) The cognitive–visual integration model determining driving safety.

Given the heterogeneous nature of PD and the complex impact of visual, cognitive, and motor deficits, proper evaluation and individualized counseling are essential for determining driving fitness and implementing strategies to mitigate driving-related risks (Álvarez, 2016). It is noteworthy that individuals with PD may exhibit heightened confidence in their visual perception, reporting greater confidence in visually guided decisions compared to older healthy controls, despite demonstrating comparable perceptual performance. This finding suggests a potential overestimation of visual reliability (Halperin *et al.*, 2021), which may result in visual hyper-dependence and contribute to impaired driving performance. Therefore, visual information plays an important role in driving performance in individuals with PD. In summary, driving safety in individuals with PD is shaped by a complex interplay of visual, cognitive, and motor factors. A comprehensive understanding of the dynamics

between these domains is imperative for the development of efficacious assessment instruments and intervention strategies that promote safer mobility and preserve autonomy in this population.

This prompts a critical question that often arises after a diagnosis: “*Is it time to stop driving?*” Current evidence presented in this chapter reveals that answer is neither simple nor universal - it depends on the individuals’ specific pattern of impairments, disease stage, and functional abilities. The diagnosis itself should not be an automatic mandate to cease driving (Classen *et al.*, 2015; Devos *et al.*, 2013a). Instead, it should signal the start of a proactive and individualized evaluation process. PD is a highly heterogeneous disorder, and its impact on driving capability is equally heterogeneous. It is imperative to note that the primary risks frequently emerge from the intricate interplay of visual, cognitive, and perceptual impairments, rather than from the more overt motor symptoms (Uc *et al.*, 2011). Therefore, the question shifts from “*Should you drive?*” to “*How is PD affecting your ability to drive safely, and under what conditions might you be at risk?*”. Addressing this inquiry necessitates a multidisciplinary evaluation that encompasses specialized assessments of vision and cognition, ideally complemented by objective instruments such as eye-tracking or driving simulations.

Notwithstanding the integrative discourse on sensorial-cognitive integration during driving in individuals with PD, significant lacunae persist regarding this subject. There is a clear need for more ecologically valid research that studies visual behavior in the complexity of real-world driving (Classen, 2014; Uc *et al.*, 2009c), and for developing practical, standardized tools that clinicians can use to assess driving fitness. Importantly, a deeper appreciation of the role of vision in driving with PD is essential. We must move beyond simply determining if

the individuals with PD can drive, and work to understand how their specific visual challenges affect their driving. This understanding serves as the foundation for the development of effective interventions, the improvement of assessments, and, most crucially, the facilitation of sensitive dialogues that assist individuals with PD and their families in achieving a balance between safety and independence.

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